31 OCTOBER 1968 K-11-68-1K

FINAL REPORT

A STUDY OF HYDROGEN SLUSH AND/OR HYDROGEN GEL UTILIZATION

Contract NAS 8-20342
(SUPPLEMENTAL PROGRAM)

VOL II
TEST PROGRAM
41.5-INCH DIAMETER TANK

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

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CRYOGENIC STAGE PROGRAMS

LOCKHEED MISSILES & SPACE COMPANY / SUNNYVALE, CALIFORNIA
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

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FOREWORD

The purpose of the effort conducted under this contract is to develop the analytical technology and capability required for preliminary stage design, or modifications of existing stages, to utilize hydrogen slush and/or gel propellants. Results of this study are intended to indicate the advantages or disadvantages of various slush hydrogen and/or gel systems as compared to those of cryogenic liquid systems, and to establish what basic research is necessary for preliminary design inputs.

The initial effort under this contract was directed to a 14-month analytical program which was completed in March 1967. During that program, detailed vehicle subsystems studies and three typical vehicle mission application studies were performed. The conclusion was that future use of hydrogen solid-liquid mixtures, i.e., slush, for space propulsion is both feasible and advantageous. Advantages are increased payload capabilities and reduction or elimination of hydrogen tank venting, depending upon the particular vehicle and the assigned mission. The conclusions of this study, efficiently and capably directed by Mr. A. L. Worlund, Fluid Thermal Systems Branch, Propulsion Vehicle and Engineering Laboratory, George C. Marshall Space Flight Center, were published in the final report, "A Study of Hydrogen Slush and/or Hydrogen Gel Utilization," NAS 8-20342, LMSC K-11-67-1, 2 Vols., March 11, 1967.

This initial program resulted in the conclusion that slush hydrogen is sufficiently attractive for further investigation. A supplemental program was initiated by Mr. Worlund to determine the practicality of applying slush hydrogen to NASA cryogenic-fueled vehicles under realistic conditions. In addition, it appeared of value to analyze the applicability of slush hydrogen to the Saturn S-IVC stage, a potential modification of the Saturn S-IVB for a manned Mars flyby mission. This stage and its suitability for this mission had been analyzed and reported by the Douglas Missile

and Space Systems Division of the Douglas Aircraft Company (now McDonnell Douglas). The Douglas study "Feasibility of Modifying the S-IVB Stage as an Injection Stage for Manned Planetary Flyby Missions," NAS 8-18032, DAC 57997, 2 Vols., May 1967, defined various possibilities for modifying the S-IVB stage. One attractive version, a 30-day S-IVC without a transtage associated with it, was selected to be studied under the supplemental slush hydrogen program. It was desired that the S-IVC performance and subsystems, as defined by Douglas for use with saturated liquid hydrogen, be evaluated using slush hydrogen. A performance comparison was desired, as well as identification of the impact of slush hydrogen on the S-IVC subsystems and mode of operation. This work has been completed and is reported in the Supplement Final Report, Volume I.

It was also concluded in the initial study program that experimental work was needed on a scale larger than that conducted by the Cryogenic Engineering Laboratory of the National Bureau of Standards at Boulder, Colorado, to determine the practical aspects of applying slush hydrogen to existing or new space vehicles. To perform this experimental work Lockheed provided a Cryogenic Vehicle Flight Simulator, a slush hydrogen manufacturing dewar, a slush hydrogen storage dewar, a 41.5-in. insulated flight-type propellant tank, and the necessary plumbing and controls located at the Lockheed Santa Cruz Test Base to provide realistic tools to conduct the experimental program. It was specifically intended to develop and verify recirculation as a practical ground-hold loading technique and to obtain data on the freeze-thaw manufacturing process for slush hydrogen. Other desirable data were slush storability and liquid withdrawal characteristics in a simulated space environment. The experimental program has been completed and is reported in the Supplement Final Report, Vol. II.

Throughout this program, close coordination was maintained with Mr. D. B. Chelton, Mr. D. B. Mann, and Mr. C. F. Sindt, National Bureau of Standards (NBS), Institute for Basic Standards, Cryogenics Division, where a related analytical and experimental program on slush hydrogen characteristics is in progress. Invaluable help was provided by these capable scientists.

The Lockheed work was performed under the direction of C. W. Keller, who is a Project Manager in the Propulsion Vehicle Systems group, Research and Development Division, Lockheed Missiles & Space Company.

Other Lockheed personnel who contributed significantly to the program were:

- Design: H. E. Johnson
  E. F. Cavey
  G. W. Capener
  Z. R. Stachon
- Thermodynamics: M. McNally
  R. M. Coston
- Instrumentation: R. M. Kocher
- Hardware Fabrication: L. M. Musil
  G. H. Steffen
  D. Kenworthy
  T. H. Bechdoldt
- Test: J. H. Young
  D. R. Stevenson
  W. L. Gidding
  L. C. Mellema
  C. V. Smith
  R. F. Blake
  R. J. Framstad

Key personnel at the George C. Marshall Space Flight Center were A. L. Worlund, Contract Technical Manager, and J. L. Vaniman, of the Fluid Thermal Systems Branch of the Propulsion and Vehicle Engineering Laboratory.

The overall manager of this program was Mr. Jack Suddreth, Program Manager, Liquid Propulsion Technology, Chemical Propulsion Division, NASA Office of Advanced Research and Technology.

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Section 1
INTRODUCTION AND SUMMARY

This volume contains details and results of a subscale tank test program performed to advance the development of slush hydrogen technology for future space vehicle applications. The test program was part of a supplemental effort to the basic contract. The primary objective of this part of the effort was to perform tests and supporting analyses to evaluate conclusions and to expand knowledge of procedures and system requirements derived from the original work under the contract. Specific objectives were to:

- Confirm that the recirculation technique for tank loading and ground-hold operations was technically valid.
- Compare predicted and measured flow characteristics such as slush mass and quality, flow rates, temperatures, and pressures during simulated ground and space operations.
- Demonstrate that helium can be used as a partial pressurant to stabilize a flight-weight tank shell containing triple-point hydrogen in a higher pressure environment.
- Determine whether or not slush mass and quality measurements can be made in a flight-type tank within accuracies required for space vehicle applications.
- Demonstrate overall system controllability and performance throughout simulated mission operations and pressure environments including:
  - Propellant loading and upgrading
  - Prelaunch holds
  - Ascent and orbital flight
  - Propellant drainage
- Demonstrate stratification effects in a flight-type tank loaded with slush in an earth-gravity environment.

- Demonstrate the effect of mixing slush hydrogen in an earth-gravity environment.
- Further evaluate the freeze-thaw process of manufacturing slush hydrogen.

To meet these objectives the 20-month supplemental test program was conducted in three tasks. In Task 1, design and analyses were performed to develop the apparatus and instrumentation needed for the demonstration tests. Parallel efforts were conducted under Lockheed funding to modify existing facilities and to develop new ones to support this work. Task 2 consisted of hardware component procurement, fabrication, and assembly of the apparatus. Finally, in Task 3, the efforts culminated in the installation and checkout of the apparatus, instrumentation, and supporting facilities, the performance of test operations, and the reduction and evaluation of recorded data.

1.1 TEST PROGRAM RESULTS

Three different slush flow tests were performed during the program. Two were of approximately 48 hr duration while the duration of the third was approximately 12 hr. All were conducted without interruption, using two 12-hr shifts of test personnel per day.

In the first flow test, the apparatus was subjected to an environmental heat load typical of cryogenic space vehicle groundhold operations in the Cryogenic Vehicle Flight Simulator. During the second and third flow tests, the simulator environment was modified to provide heat loads typical of ascent and orbit operations.

The recirculation technique of loading and maintaining a tank with subcooled liquid and slush was demonstrated in all three flow tests. Also, in each of the three tests, predicted and measured flow characteristics were compared, liquid and slush mass and quality measurement accuracies were assessed, stratification effects were observed, and the overall system controllability and performance was evaluated. In the second and third tests, the effects of mixing and the characteristics of subcooled liquid drainage were observed.

During the program, the freeze-thaw process of manufacturing slush hydrogen was thoroughly evaluated. This was done using existing equipment and technicians with no prior specialized training, for the first time on a nonlaboratory basis. A total of 145 0.132-m^3 (35-gal) batches of slush totaling more than 18.9 m^3 (5000 gal), were manufactured and transferred to accomplish the program.

Approximately 2.87 m^3 (760 gal) of slush were accumulated after manufacture and stored in a facility dewar during preparations for each of the first two flow tests. During these tests, continuous flow was then supplied from the storage dewar to the test tank. Approximately 1.32 m^3 (350 gal) of slush were manufactured and transferred directly from the manufacturing dewar into the test tank during the third flow test. Since the slush was supplied after manufacture of 10 individual batches, flow into the test tank was intermittant during this third test.

During transfer operations throughout the program, severe thermal oscillations occurred at transfer line bayonet fittings and valves. Significant quantities of the solid being transferred were melted by the excessive heat load imposed on the system at each point where the oscillations occurred. Nonethless, substantial quantities of slush were successfully transferred, particularly in the last two flow tests after some modifications were made to the facility hardware. All major objectives of the program were achieved, and many unforeseen additional benefits were derived in terms of basic knowledge and experience needed to further develop the technology.

Considerable effort was expended early in the program during the design and procurement subtasks to obtain the high quality hardware needed to transfer triple-point hydrogen. However, detailed knowledge concerning the actual performance of the hardware selected, and the true scaling effects for a facility of this size were not previously available. As a direct result of this experience, additional emphasis can now be placed on design, specification,and quality control of transfer system hardware so that this problem can be solved for all future applications.

No measurable quantity of slush was transferred into the test tank during the first flow test because of the high heat load on the transfer system. However, the tank was loaded with slightly subcooled liquid, and it was determined that the apparatus, instrumentation, and data-acquisition systems were functioning properly. At one point during the recirculation flow for this test, the average bulk density of the hydrogen in the tank was determined to be approximately 65.1 kg/m^3 (4.061 lb/ft^3). Based on the pressure and temperature of the fluid in the tank at that time, it was shown that bulk boiling conditions existed. Thermal stratification measured by platinum thermometers in the tank, was shown to be on the order of 2.2°K (4°R) between the liquid interface and the bottom of the tank. Some difficulty was experienced in this test regarding accurate control of the liquid-vapor interface position as recirculation was initiated. This was found to be due to insufficient prechilling of the recirculation line.

The second flow test was the most successful of the three in terms of achieving specific program objectives. Reduced data obtained during this test show that slush qualities of approximately 21.3 percent or higher were achieved and measured. In addition, the slush was stored without venting or excessive pressure buildup during the space storability phase of the test. Mixing was shown to be a relatively effective technique for controlling tank pressure with liquid in the tank; however, no mixing data were obtained with slush in the tank.

During propellant draining at the conclusion of the second flow test, data were obtained that in general show good drainage characteristics can be expected using subcooled liquid hydrogen. The most significant result of the drain test was the demonstration that the drainline must be adequately prechilled to prevent initial vapor formation with resulting choked-flow conditions and erroneous flowmeter data due to two-phase flow.

During the third flow test, successful loading of slush using the recirculation technique with intermittent flow was again demonstrated.

In this test, slush qualities ranging from 3 to 21 percent were calculated from data recorded during the fourth through the tenth batch transfers. In addition, the technique used to prechill the recirculation line (modified from that used in previous tests) was shown to be successful. Storability, mixing, and propellant draining sequences were also performed during the third test with results similar to those obtained on the second test.

1.2 CONCLUSIONS

The major conclusions that resulted from observations made during the three flow tests, and evaluation of the recorded data obtained from them, are as follows:

- The recirculation technique of loading slush into a flight-weight tank during groundhold operations is technically valid
- Flow characteristics of slush such as mass and quality, flow rate, temperature, and pressure can be adequately predicted with present analytical techniques
- Helium can be used as a partial pressurant to stabilize a flight-weight tank shell that contains triple-point hydrogen
- Slush mass can be measured within ±1 percent and slush quality can be measured within ±10 percent using state-of-the-art instrumentation in a ground test apparatus*
- Significant stratification will exist in a flight-type tank containing slush hydrogen when subjected to earth-gravity and high heat load environments
- Mechanical mixers can probably be used to control pressure without venting in a tank containing slush hydrogen provided they are properly designed and located in the tank
- The freeze-thaw process of manufacturing slush hydrogen is practical, efficient, and can readily be used to manufacture large quantities of slush by technicians with no prior specialized training

*Flight vehicles will require a different type of mass-measurement instrumentation than the weighing system used during this program. The measurement accuracy of instrumentation applicable to flight vehicles will require verification in future tests.

It has been shown throughout the contract study program that future use of triplepoint liquid and slush hydrogen in space propulation systems could significantly improve hydrogen storability characteristics and performance. It is clear from the results of these subscale tests, however, that more work is needed to develop design criteria and suitable hardware for vehicle launch-site slush facilities before subcooled hydrogen fuels can be used successfully. In particular, detailed design tradeoff studies and further tests should be performed to develop transfer system plumbing that is more suitable for slush service. Hardware components that should be improved in such a development include vacuum-insulated lines, bayonet fittings, and valves. Design, analytical, and test work is also needed to further develop existing instrumentation components to improve the ability to measure slush mass and quality, slush-liquid and liquid-vapor interface position, and temperatures near the triple-point of hydrogen.

1.3 RECOMMENDATIONS

The following recommendations are offered based on the knowledge and experience gained during this test program:

- Design tradeoff studies and tests should be undertaken to develop suitable slush transfer system plumbing components, particularly bayonet fittings and valves.
- Detailed preliminary design studies should be undertaken to develop design criteria for launch site slush manufacturing, storage, and transfer facilities.
- All future study efforts should be expanded to include other promising sub-cooled and/or slush propellants such as methane.
- The subscale test program initiated during this supplemental work should be continued to further develop and demonstrate scaling laws for groundhold recirculation, slush storability, mixing, and draining in flight-type tanks when exposed to space vehicle environments.
- Work should be continued to develop and improve instrumentation components and techniques for measuring slush mass and quality in a flight-type tank.

Section 2
FACILITY DESCRIPTION

The Cryogenic Vehicle Flight Simulator located at Lockheed's Santa Cruz Test Base was used to perform this contract test program. This facility complex, designed and built by Lockheed at a cost of several million dollars, is an advanced vehicle flight simulator which specializes in the use of advanced cryogenic propellants. An aerial view of the complex is shown in Fig. 2-1. Specific areas of the complex that were pertinent to the program include (1) the test pad area, where the vacuum chamber (flight simulator), vacuum-pumping systems, and the slush hydrogen facilities are located, (2) the control and instrumentation building, where the data-acquisition equipment described in Section 4 is located, and (3) the cryogen and pressurant storage area, where the 49.2-m^3 (13,000-gal) LH_2 storage dewar is located. These areas are described in greater detail in the following paragraphs. Numerous supporting systems that were also significant to the program are integrated throughout the complex. These include systems that provide for LN_2 and GN_2 storage and distribution, LH_2 and GH_2 dump, disposal and vent, electrical power distribution and control, fire detection and warning, water deluge, closed-circuit television, voice communication, and other pertinent functions. This Cryogenic Vehicle Flight Simulator is capable of simulating ground hold, launch and ascent, and space operating environments (except for low gravity and high gravity conditions) for vehicles up to 400-cm (156-in.) in diameter, and can be readily modified to accommodate vehicles up to 650-cm (260-in.) in diameter

2.1 TEST PAD AREA

The test pad area contains (1) the cryogenic vacuum chamber installation, wherein the slush hydrogen test apparatus was located, (2) the vacuum-pumping systems, and (3) the slush hydrogen manufacturing, transfer, and storage systems. The area is surrounded by a trussed A-frame enclosure 22.9 m (75 ft) in height. The test pad is

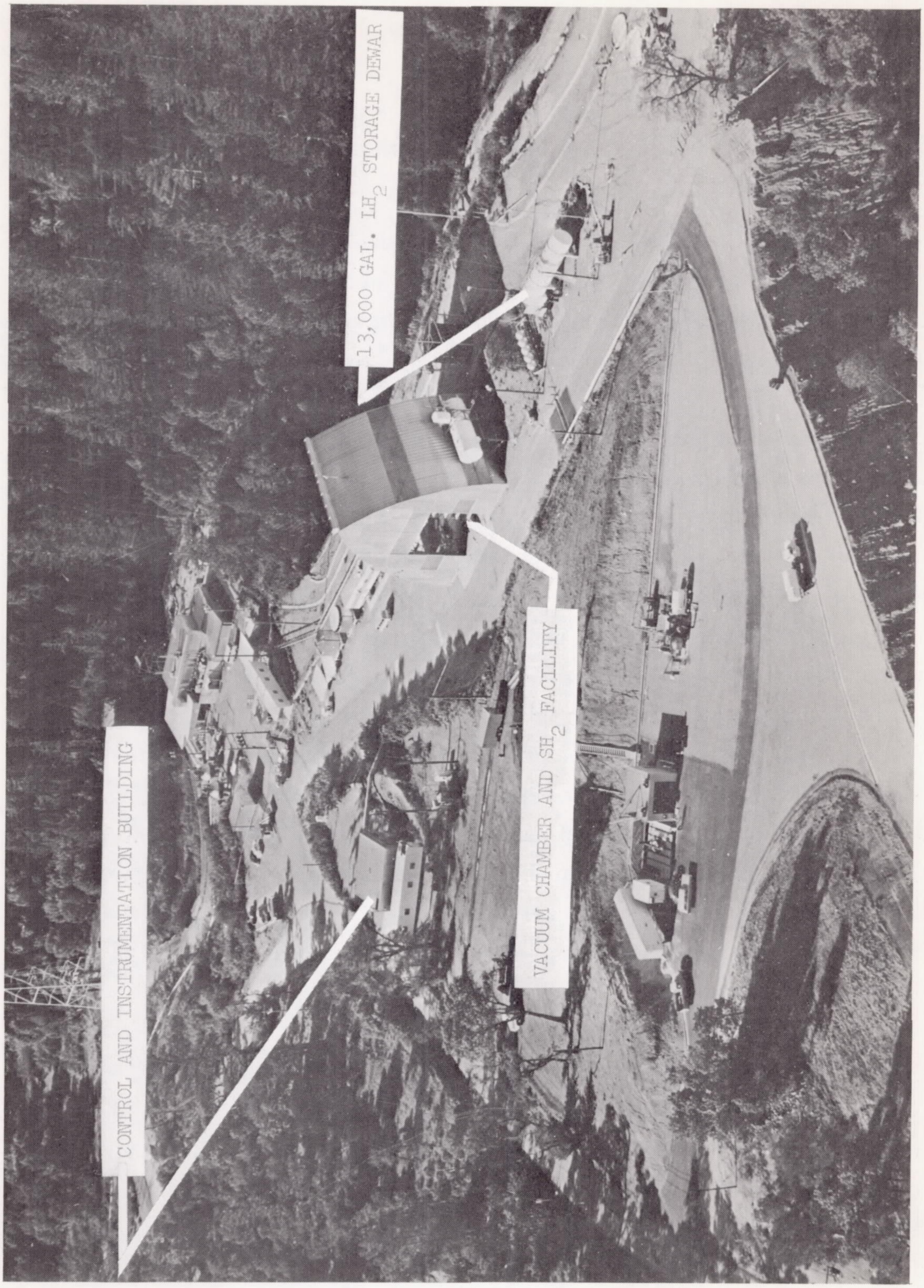


Fig. 2-1 Aerial View of Cryogenic Test Complex

constructed of reinforced concrete, is approximately 24.4 m (80 ft) in length by 18.3 m (60 ft) in width, and contains tiedown rails, spaced every 0.9 m (3.0 ft) which run approximately half its length. A 3.6 m (12 ft) by 4.9 m (16 ft) by 5.5 m (18 ft) reinforced concrete blast wall, as well as an 11 m (36 ft) by 21 m (69 ft) by 4.6 m (15 ft) sand and dirt revetment, are located between the pad area and the cryogen and pressurant storage area.

Inside the A-frame enclosure, a 9072 kg (10-ton) capacity hoist with a 19.2 m (63-ft) hook clearance is available to handle test and facility hardware. The hoist is mounted on a momorail and has a 21.3 m (70-ft) traverse. A T-pad of reinforced concrete houses the instrumentation junction box, the controls junction box, and the electrical distribution box.

2.1.1 Cryogenic Vacuum Chamber Installation

The cryogenic vacuum chamber used for this test program is 4.9 m (16 ft) in inside diameter and approximately 7.6 m (25 ft) in inside height. It can accommodate, in a vertical position, a test specimen 4 m (13 ft) in diameter and 5.2 m (17 ft) in length. The chamber is composed of four sections which include a base, two intermediate sections, and an upper section. The base is cylindrical and has an inside height of 1.518 m (4 ft 11-3/4-in.). This section contains 25 ports for plumbing and instrumentation connections. The two intermediate removable cylindrical sections are each 2.121 m (6 ft 11-1/2-in.) in height. Only one of these was installed during reassembly of the chamber after installation of the slush test apparatus. The upper section is composed of a cylindrical segment 0.635 m (2 ft 1 in.) in height and an ellipsoidal head that contains five ports for plumbing and instrumentation connections. All chamber sections, including the base floor and all manifolds, flanges, ports, and fittings are constructed from 304 stainless steel. The surfaces exposed to vacuum conditions were ground and polished to achieve a simulated No. 4 finish. Double O-ring flanges provide sealing between chamber sections, around all instrumentation and plumbing ports, and around the access door located in the base section. The chamber

was designed to maintain a minimum pressure of 1.0×10^{-6} torr for extended test periods and a maximum pressure of 0.06895 N/cm^2 gage (0.1 psig) without leakage. It has actually operated below this minimum pressure for long duration tests. Various vehicle sizes can be accommodated in the facility by merely changing the diameter and/or the number of the intermediate cylinder sections.

The vacuum chamber is located near the center of the test pad area and inside the A-frame enclosure as shown in Fig. 2-2. The 2.794 m (110-in.) major-diameter ellipsoidal tank shown in the figure is one that was fabricated and used for a related, previously completed hydrogen test program.

2.1.2 Vacuum-Pumping Systems

The vacuum-pumping systems that were installed to service the cryogenic vacuum chamber include a two-stage steam ejector system and a high-vacuum mechanical/diffusion pumping system that can be used either in combination or separately. The steam ejector system can provide sufficient pumping rates to accurately simulate flight vehicle ascent pressure profiles from atmospheric pressure down to approximately 1.03 N/cm^2 (1.5 psia), corresponding to approximately 15,850 m (52,000 ft) in altitude. Pressure environments from atmospheric pressure to 1.0×10^{-6} torr can be achieved with use of the high-vacuum system, but require longer pumping times than those that would be needed to simulate the ascent pressure profile for space vehicles above 15,850 m (52,000 ft) altitude. Only the high-vacuum mechanical/diffusion pumping system was used during this program.

The high-vacuum mechanical/diffusion pumping system consists of two mechanical roughing pumps (further described in subsection 2.1.3.2), a 36.8 m^3/min (1300-cfm) displacement blower, and two 121.9 cm (48-in.) diffusion pumps. The two mechanical pumps can be operated separately from atmospheric pressure down to approximately 1.0×10^{-2} torr, and in series with the blower to 1.0×10^{-3} torr. Both the mechanical roughing pumps and the blower serve as fore-pumps for the two diffusion pumps. The latter are nominally started at a chamber pressure of approximately 1.0×10^{-1} torr, and can ultimately achieve a pressure as low as 1.0×10^{-6} torr.

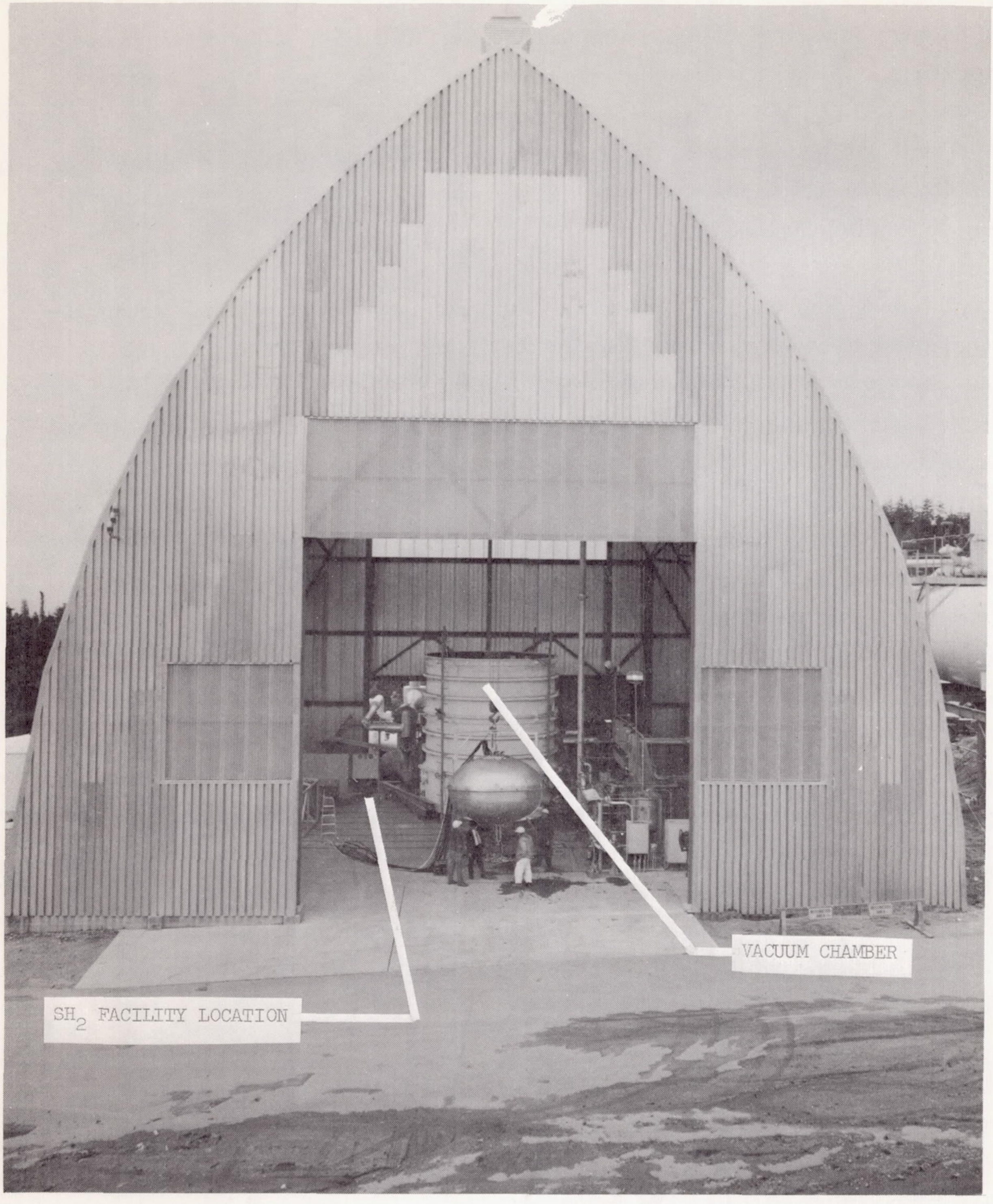


Fig. 2-2 Cryogenic Flight Simulator (Photograph taken before installation of slush facilities.)

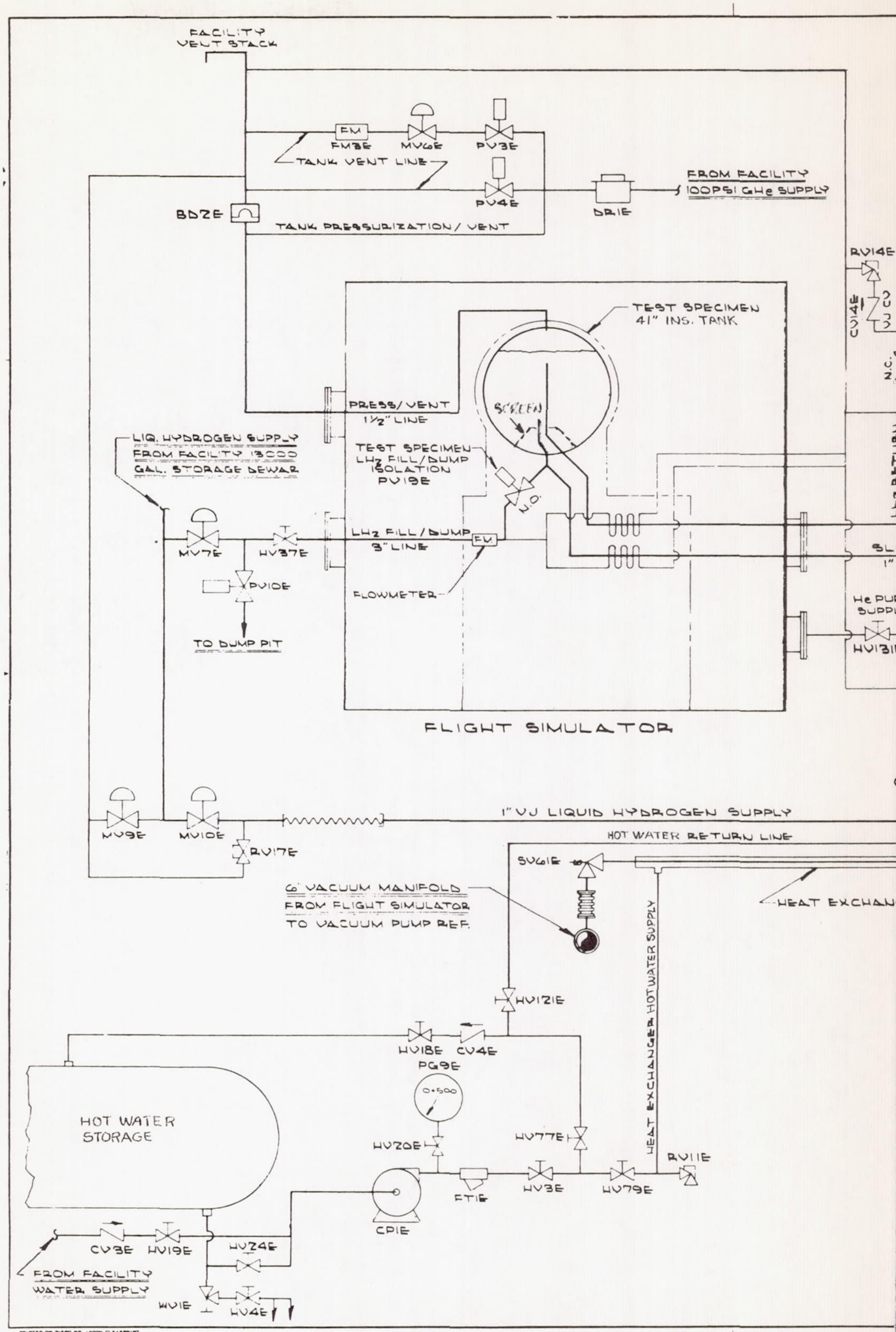
When the high-vacuum pumping system is operated independent of the steam ejector system it can evacuate the dry empty chamber from 1.0 psia to 1×10^{-4} torr in approximately 2 hr, or from atmospheric pressure to 1.0×10^{-6} torr in approximately 4 hr. The two diffusion pumps can provide a net pumping speed of 30,000 liters/sec (1059 ft^3/sec) at the chamber wall when fully warmed up. Warmup time is approximately 45 min for these pumps.

During this test program, the high-vacuum pumping system was used to evacuate the chamber prior to backfilling with GHe for the ground hold test sequences, and again during the ascent/orbit test sequences. In addition, the two mechanical roughing pumps were used to manufacture slush hydrogen for the tests as described in Sections 6 and 7. During manufacture of slush, hot water was supplied from a steam accumulator to a heat exchanger located in the vacuum-pumping line between the slush manufacturing dewar and the inlet to the mechanical roughing pumps. This heat exchanger served to warm the hydrogen vapor pumped from the manufacturing dewar to near-ambient temperature before it entered the pumps.

2.1.3 Slush Hydrogen Manufacturing, Transfer, and Storage Systems

The primary elements of the slush hydrogen manufacturing, transfer, and storage systems are (1) the slush hydrogen manufacturing dewar, (2) the mechanical vacuum pumps, (3) the pressurant gas heat exchanger, (4) the slush manufacturing dewar vent gas heat exchanger, (5) the portable 1.89 m^3 (500-gal) LH_2 dewar, and (6) the 3.04 m^3 (804 gal) slush storage dewar. Figure 2-3 is a schematic of these systems as installed prior to the first slush flow test. A photograph of the installation at that time is shown in Fig. 2-4.

Vacuum-jacketed, multilayer-insulated stainless-steel lines were provided throughout the facility for handling liquid and slush hydrogen. Standard cryogenic safety devices including relief valves, rupture discs, and pressure switches were installed in all systems. Special provisions were incorporated into all slush transfer lines to minimize thermodynamic oscillation problems. For example, close-tolerance check valves were provided on relief valve risers, and close-tolerance cold nose seals were provided on


FACILITY VENT STACK
FM
FM3E
MV6E
PV3E
TANK VENT LINE
PV4E
DR1E
FROM FACILITY 100PSI GHe SUPPLY
BD2E
TANK PRESSURIZATION / VENT
RV14E
CV14E
N.C.
TEST SPECIMEN 41" INS. TANK
SCREEN
PRESS/VENT 1½" LINE
LH2 RETURN
LIQ. HYDROGEN SUPPLY FROM FACILITY 13000 GAL. STORAGE DEWAR
TEST SPECIMEN LH2 FILL/DUMP ISOLATION PV19E
N.O.
MV7E
HV37E
LH2 FILL/DUMP 3" LINE
FM
PV10E
FLOWMETER
TO DUMP PIT
He PUR SUPPL
HV13E
FLIGHT SIMULATOR
MV9E
MV10E
RV17E
1" VJ LIQUID HYDROGEN SUPPLY
HOT WATER RETURN LINE
SV61E
6" VACUUM MANIFOLD FROM FLIGHT SIMULATOR TO VACUUM PUMP REF.
HEAT EXCHAN
HEAT EXCHANGER HOT WATER SUPPLY
HV12E
HV18E
CV4E
PG9E
0-500
HOT WATER STORAGE
HV20E
HV77E
HV3E
HV79E
RV11E
FT1E
CP1E
CV3E
HV19E
HV24E
FROM FACILITY WATER SUPPLY
HV1E
HV4E

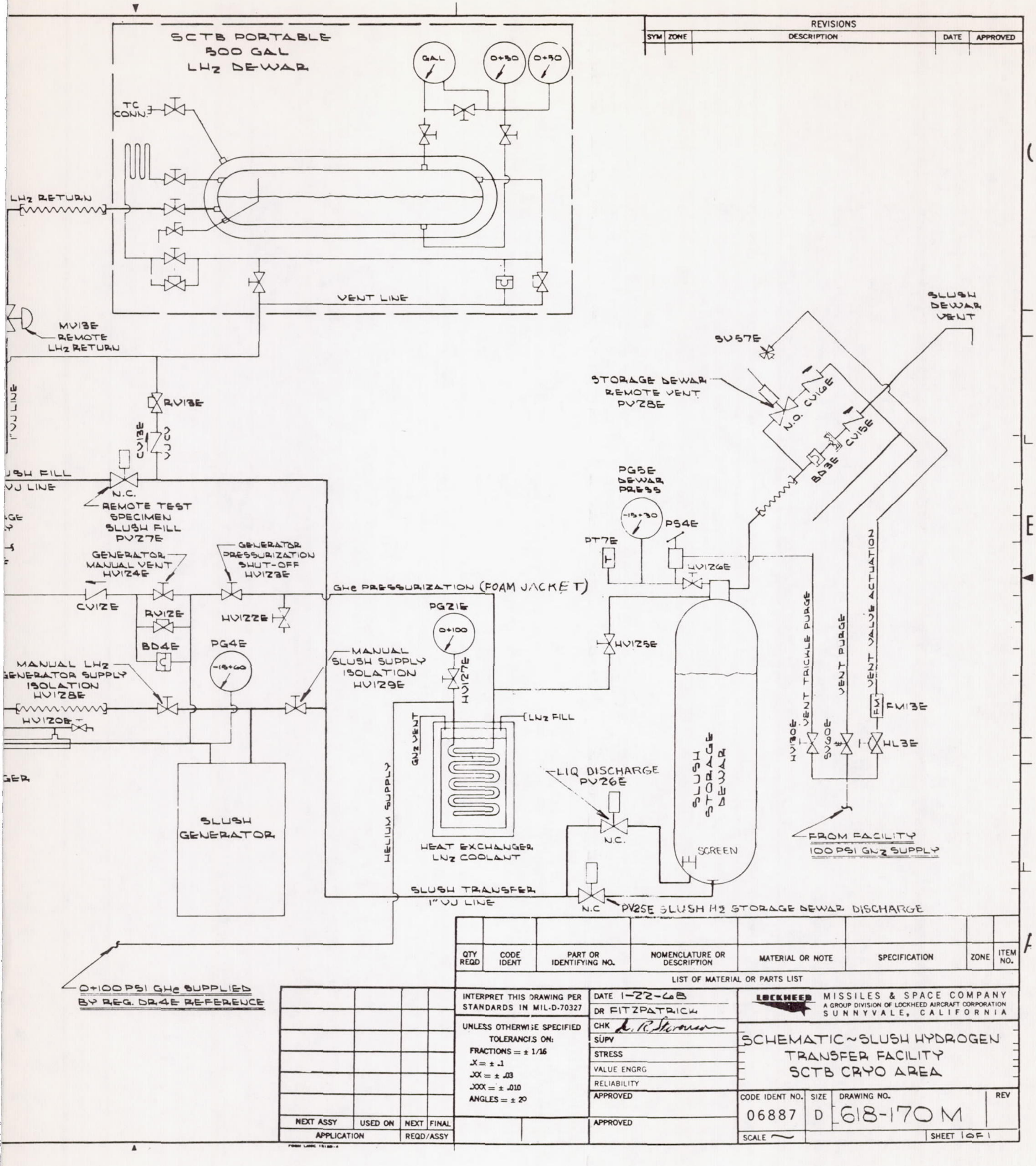


Fig. 2-3 Schematic of Slush Hydrogen Manufacturing, Transfer, and Storage Systems Before Modification

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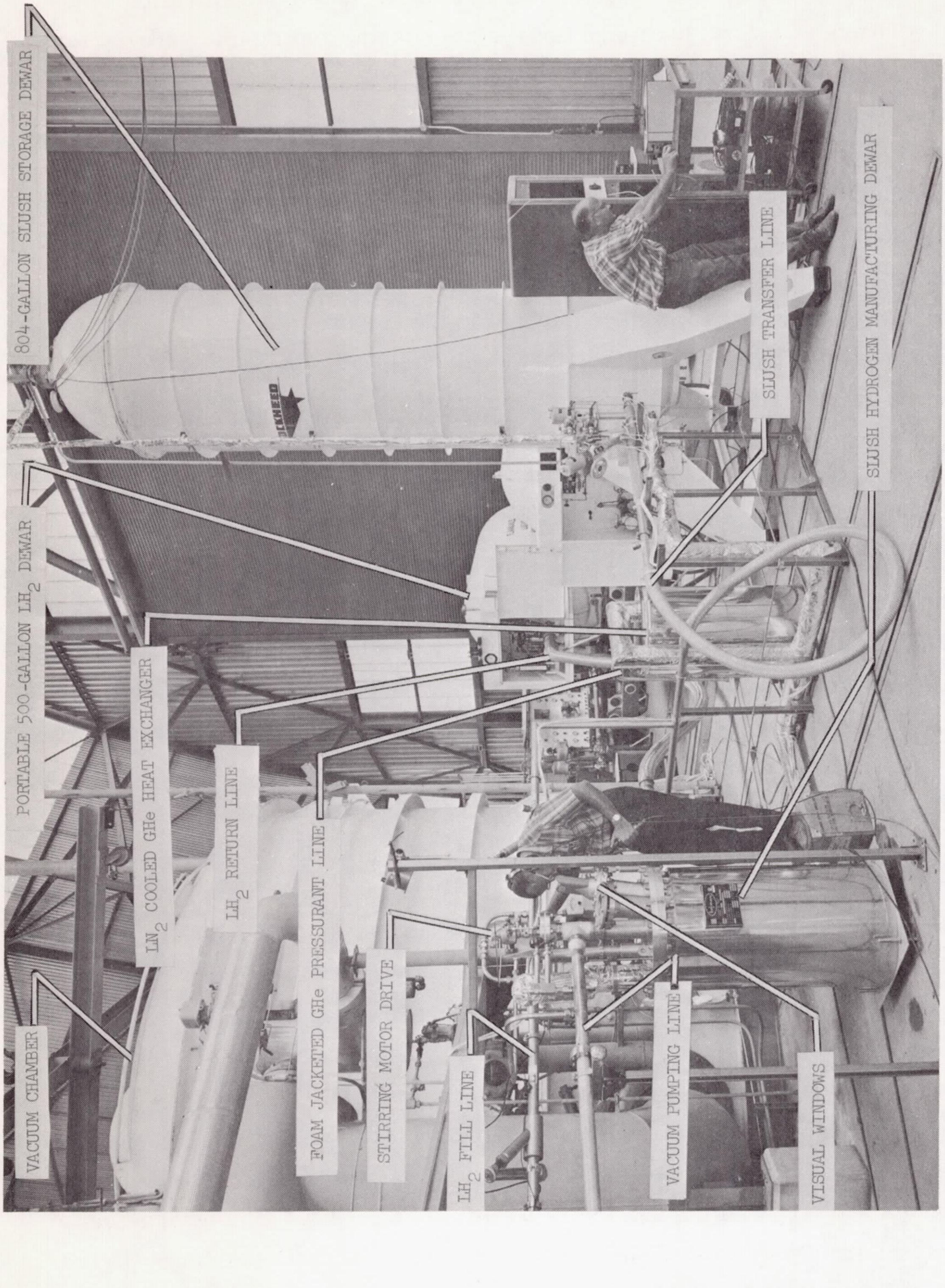


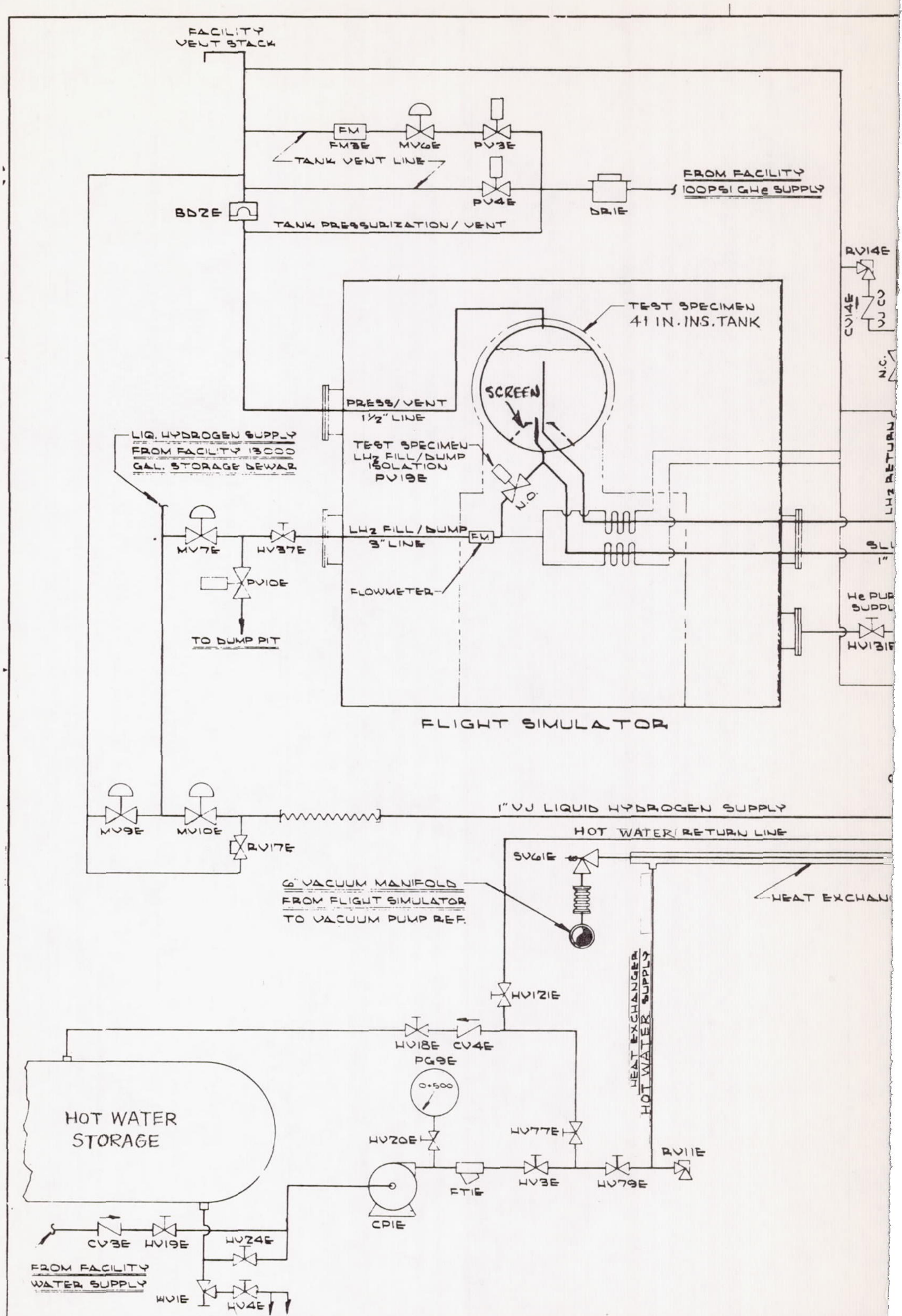
Fig. 2-4 Installation of Slush Test Facility Before Modification

all bayonet fittings. Facility GN_2 was used to inert all systems before chilldown and filling with hydrogen. Gaseous hydrogen for system purging and liquid hydrogen for slush manufacture were supplied from the 49.21 m^3 (13,000-gal) storage dewar described in subsection 2.3.1.

Prior to procuring the facility items unique to the slush hydrogen program, NBS CEL personnel (Boulder, Colo.) were extensively consulted. Their knowledge of slush hydrogen was completely utilized in the design of the LMSC slush facility. After installation, NBS personnel inspected and approved the facility. During the first slush flow test (Section 7.1), it was determined that severe thermal oscillations were occurring in the bayonet fittings and around valve stems. The heat transfer to the slush during flow was estimated to be at least an order of magnitude greater than that previously predicted by analysis. These systems were, therefore, modified between the first and second slush flow tests to reduce the heat transfer to the slush as much as possible without completely redesigning and refabricating the system. Modifications included (1) replacement of the loop of flexible vacuum-jacketed transfer line shown in Fig. 2-4 with a hard vacuum-jacketed elbow section, (2) shortening of the helium pressurant lines and replacement of the previous foam and fiberglass insulation around them with liquid nitrogen jackets, (3) installation of a bleed valve to the GHe pressurant line near the top of the storage dewar, and (4) installation of external foam insulation on all slush transfer line bayonet fittings.

The problems in transfer line design that were encountered are attributed to the lack of suitable scaling data over that obtained by NBS personnel in their laboratory-type facility. Also, these design problems were significantly magnified by the relatively large dimensional tolerances of the actual plumbing hardware that was procured and installed.

It was found during the manufacture of slush for the second flow test that the presence of the insulation on the bayonet fittings reduced the temperature of the Butadiene O-ring seals below their resilient sealing capability. This resulted in leakage out of the lines, and the insulation was subsequently removed. The final system configuration is shown schematically in Fig. 2-5, and in the photograph of Fig. 2-6.



FACILITY VENT STACK
FM
FM3E
MV6E
PV3E
TANK VENT LINE
PV4E
DR1E
FROM FACILITY
100PSI GHe SUPPLY
BD2E
TANK PRESSURIZATION / VENT
RV14E
CV14E
TEST SPECIMEN
41 IN. INS. TANK
SCREEN
PRESS/VENT
1½" LINE
LIQ. HYDROGEN SUPPLY
FROM FACILITY 13000
GAL. STORAGE DEWAR
TEST SPECIMEN
LH2 FILL/DUMP
ISOLATION
PV19E
N.O.
N.C.
LH2 RETURN
MV7E
HV37E
LH2 FILL/DUMP
3" LINE
FM
PV10E
FLOWMETER
TO DUMP PIT
He PUR
SUPPL
HV13IE
FLIGHT SIMULATOR
1" VJ LIQUID HYDROGEN SUPPLY
MV9E
MV10E
RV17E
HOT WATER RETURN LINE
SV6IE
6" VACUUM MANIFOLD
FROM FLIGHT SIMULATOR
TO VACUUM PUMP REF.
HEAT EXCHAN
HV12IE
HEAT EXCHANGER
HOT WATER SUPPLY
HV18E
CV4E
PG9E
0-500
HOT WATER
STORAGE
HV20E
HV77E
RV11E
FT1E
HV3E
HV79E
CP1E
CV3E
HV19E
HV24E
FROM FACILITY
WATER SUPPLY
HV1E
HV4E

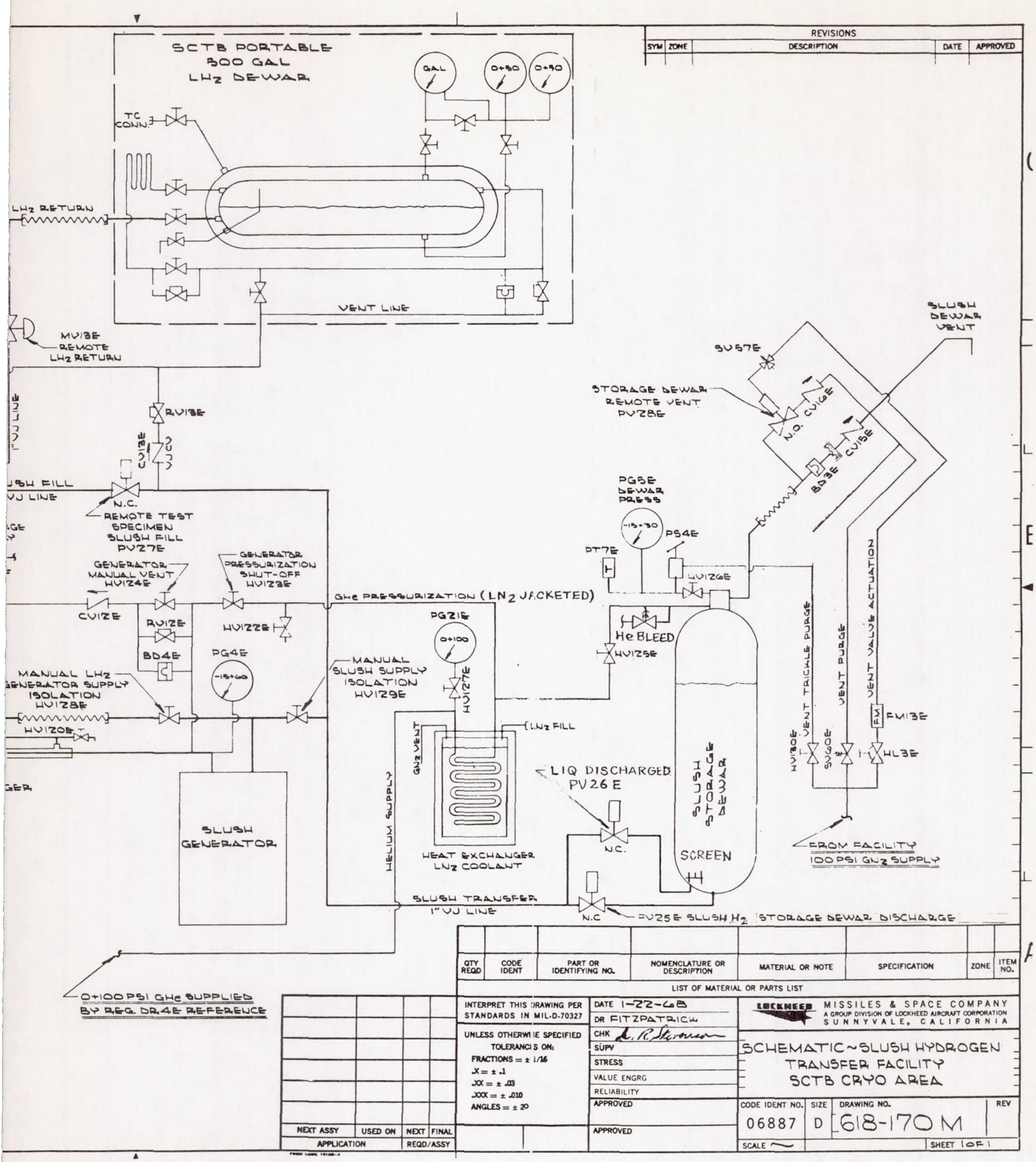


Fig. 2-5 Schematic of Slush Hydrogen Manufacturing, Transfer, and Storage Systems After Modification

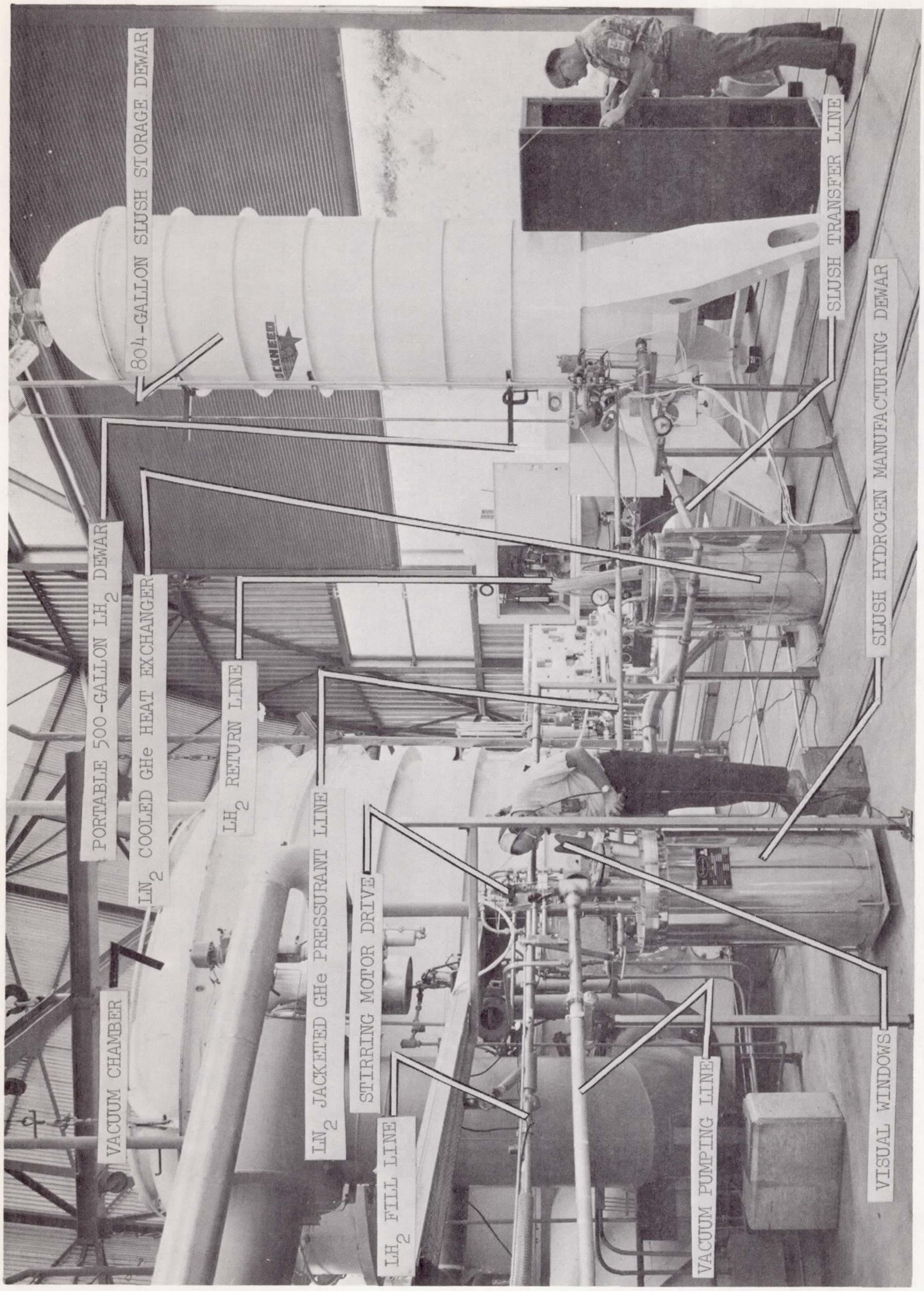


Fig. 2-6 Installation of Slush Test Facility After Modification

2.1.3.1 Slush Hydrogen Manufacturing Dewar. The slush hydrogen manufacturing dewar consists of a vacuum-jacketed, multilayer-insulated 0.25 m^3 (66-gal) Hofman cryogenic dewar, 55.9-cm (22 in.) in diam and 101.6-cm (40-in.) high. The Hofman No. 3010 ASME Code stamped dewar is rated at a 137.9 N/cm^2 gage (200-psig) maximum working pressure, and is equipped with a bolt-on cover. The cover and internal components of the dewar are shown in Fig. 2-7. This flat cover 3.81-cm (1-1/2 in.) thick is rated at a 34.5 N/cm^2 gage (50-psig) maximum working pressure, and is equipped with two 10.2-cm (4.0-in.) diam pyrex windows and three lifting lugs. The windows are mounted on tubular standoffs 25.4-cm (10-in.) long fabricated from schedule 5,300 series stainless steel pipe. The cover is penetrated by a 2.54-cm (1.0-in.) diam vacuum-jacketed fill and drain line and a 7.6-cm (3.0-in.) diam vacuum-pumping line through integrally-welded fittings. The cover and both windows are sealed with O-ring, bolted flanges. The dewar, cover assembly, and both line penetrations were also fabricated from 300 series stainless-steel material.

The manufacturing dewar cover is insulated from the dewar ullage space by a fiberglass-coated layer of polyurethane foam 15.2-cm (6-in.) thick attached to the inside of the cover. A low-speed mechanical agitator was provided inside the dewar (Fig. 2-7) to achieve thermal and physical mixing of the liquid and slush hydrogen during manufacturing and transfer operations. The agitator is driven by a Gast Manufacturing Corporation Model 4 AM-FRV-13A variable-speed air motor that is mounted externally on a flange of the 7.6-cm (3.0-in.) diam. vacuum-pumping line. The agitator drive shaft penetrates the flange through a National Research Corporation rotary motion feedthrough, Model 13214.

2.1.3.2 Mechanical Vacuum Pumps. The two mechanical roughing pumps that were mentioned in subsection 2.1.2 are used not only as an integral part of the high-vacuum pumping system for the vacuum chamber, but also, when isolated from the high-vacuum pumping system, to manufacture slush hydrogen. One is a Beach-Russ Model

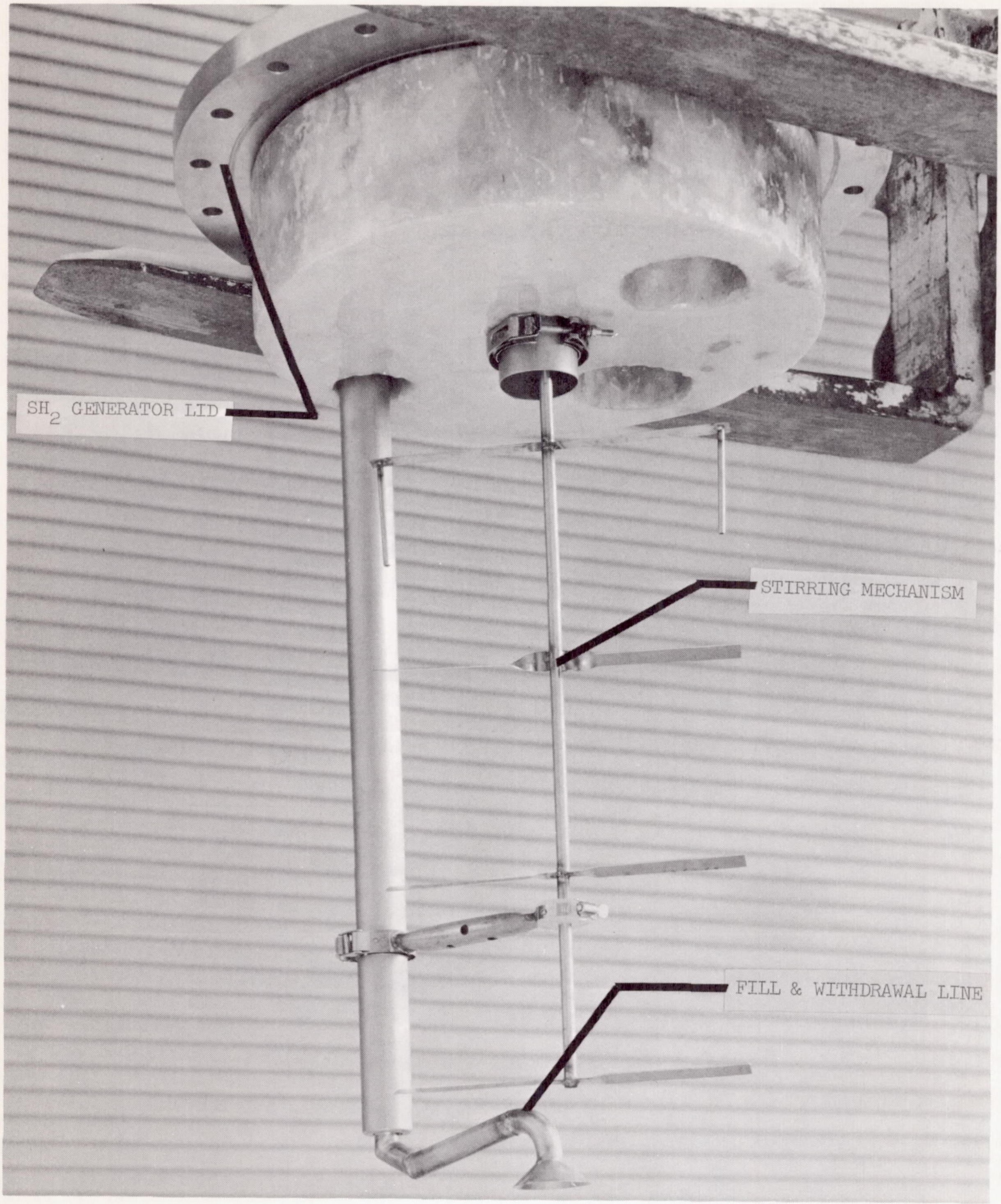


Fig. 2-7 Slush Manufacturing Dewar Internal Components

M651 pump rated at 7.08 m^3/min (250 cfm) at a 0.5-torr pressure; the other is a Stokes Model 412H – 11 pump rated nominally at 7.93 m^3/min (280 cfm). These pumps can be isolated from the slush manufacturing dewar, when desired, by a Heraeus-Englehard pneumatically-operated shutoff valve located just upstream of the pump inlet manifold. The solenoid actuator for this valve is controlled with a remote switch located adjacent to sluch manufacturing dewar.

2.1.3.3 Pressurant Gas Heat Exchanger. A liquid nitrogen heat exchanger was provided to chill GHe pressurant in order to minimize melting of slush hydrogen in the manufacturing and storage dewars during transfer operations. The LN_2 bath is contained in a Sulfrain stainless steel, vacuum-jacketed dewar, 55.9-cm (22 in.) in diam and 101.6-cm (40 in.) high. It is pressure-rated at 10 psi and is equipped with a brass alloy cover 0.953-cm (3/8-in.) thick having four penetrations. Two of the penetrations are 2.54-cm (1.0-in.) diam, and provide for LN_2 fill and venting. The other two penetrations are of 1.27-cm (1/2-in.) diam and provide for connection of a 15.24-m (50-ft) coil of 1.27-cm (1/2-in.) copper tubing installed internally to an ambient GHe supply line from the facility, and to the cold pressurant line. The latter was initially foam-insulated between the heat exchanger outlet and the inlets to the slush manufacturing and storage dewars, but was subsequently modified to provide LN_2 jackets. The heat exchanger installation can be seen in Figs. 2-4 and 2-6.

2.1.3.4 Slush Manufacturing Dewar Vent Gas Heat Exchanger. The slush manufacturing dewar vent gas heat exchanger was fabricated from 300 Series stainless steel and is of counter-flow design. It is 6.1-m (20 ft) long with an inner pipe diameter of 5.08-cm (2 in.) and an outer shell diameter of 7.62-cm (3 in.). Hot water is supplied at 82.3° C (180° F) from the vacuum-pumping system steam accumulator and is passed through the exchanger at approximately 1262 cm^3/sec (20 gpm). It was designed to transfer 70.32 kw (4000 Btu/min) to the hydrogen vent gas before the

gas enters the mechanical vacuum pumps at a design temperature of 15.6°C (60°F). The hot water supply line is equipped with a flow control and a 86.2-N/cm^2 (125-psi) relief valve. A dresser coupling was installed in the inner pipe to compensate for thermal expansion and contraction of the pipe.

2.1.3.5 Portable 1.89-m^3 (500-gal) LH_2 Dewar. The portable 1.89-m^3 (500-gal) vacuum-jacketed LH_2 dewar was used in the system as an accumulator or storage container for LH_2 as it was returned from the test apparatus tank. The cylindrical vessel is truck-mounted and equipped with a self-pressurization coil capable of vaporising LH_2 from the inner vessel to supply a working pressure up to 69.0-N/cm^2 gage (100 psig) when desired. Vacuum-jacketed bayonet fittings are used with the slush system vacuum-jacketed transfer lines. The dewar was connected to a facility vent system when installed for this test program.

2.1.3.6 3.04-m^3 (804-gal) Slush Propellant Storage Dewar. The slush propellant storage dewar is a recently-developed vacuum-jacketed, multilayer-insulated cryogenic storage vessel. It was designed and fabricated by Lockheed specifically to store and supply liquid or slush cryogens for this and other test programs. Significant design features include (1) a vertical orientation, (2) cylindrical double-wall shells with hemispherical heads, (3) accessibility to both inner and outer vessels, (4) a low environmental heat rate, (5) withdrawal of either liquid or slush when desired, (6) separate liquid and slush level-sensing instrumentation, and (7) provisions for future addition of visual access to the inner vessel, and for future conversion to a high-capacity slush-manufacturing dewar.

The dewar is supported by four structural legs that are bolted to the base of the outer shell. It is approximately 1.22 m (4 ft) in diam and 5.49 m (18 ft) in overall height. The capacity of the inner vessel is approximately 2.89 m^3 (764 gal) when 95 percent full, and 3.04 m^3 (804 gal) when 100 percent full, at 13.9°K (25°R). It was installed

near the cryogenic vacuum chamber, adjacent to the pressurant gas heat exchanger as shown in Figs. 2-4 and 2-6.

The inner and outer cylindrical shells of the dewar were fabricated from 0.64-cm (1/4-in.) thick 2219-T351 aluminum plate stock. The hemispherical bulkheads were spin-formed from 2219-T351 plate stock. Cylindrical sections were rolled and welded, and the hemispherical heads were power-spin-formed. Nominal inside diameters of the inner and outer shells are 105.4 cm and 116.8 cm (41.5 in. and 46.0 in.), respectively. The outer shell is stiffened with external circumferential rings that were integrally welded to the shell during assembly. The upper, outer hemisphere is bolted to the outer cylindrical section with mating O-ring flanges, and is removable for access to the vacuum annulus and to the inner vessel. A 48.3-cm (19-in.) diam. O-ring-sealed access cover was also provided in the lower, outer hemisphere for access to inter-shell structural supports and plumbing components. A 25.4-cm (10-in.) diam. spring-loaded O-ring-sealed plate was provided in the center of the lower access cover that will serve to relieve any inadventent over-pressurization of the annular space exceeding approximately 0.34 N/cm^2 (0.5 psia).

Four pairs of tubular fiberglass support struts provide the structural attachment of the inner and outer vessels at the bottom of the dewar. Each strut is approximately 3.18 cm (1-1/4 in.) diam. and 25.4 cm (10 in.) long, and is attached through stainless-steel end fittings. These struts are attached to the inner vessel at four points spaced at 90 deg intervals on a Y-ring flange integrally-welded into the inner vessel shell. They are attached to the outer vessel shell at eight points, and transmit vertical, horizontal, and torsional loads directly through the outer vessel shell into the four support legs. A truncated fiberglass support cone provides structural attachment of the inner and outer vessels at the top of the dewar. The periphery of this cone is bolted to the outer cylindrical shell at the O-ring flange. The center of the cone was cut out and flanged to provide a sliding cylindrical supporting surface for the inner vessel access cover flange. The sliding support was designed to accommodate thermal expansion and contraction of the inner vessel without restraint and, therefore, transmits only horizontal loads from the inner vessel to the outer vessel shell.

A 48.3-cm (19-in.) diam. access cover was provided in the upper hemispherical head of the inner vessel shell. This cover was fitted with two 12.7-cm (5-in.) diam. openings located on either side of a third 10.2-cm (4-in.) diam opening in the center. The 12.7-cm (5-in.) diam openings are sealed with temporary blank stainless-steel plugs, and were provided for future installation of glass viewports. The 10.2-cm (4-in.) diam opening accommodates the pressurization and vent line. Four 3.73-cm (1.47-in.) diam. openings were also provided through the cover to accommodate electrical feedthrough connectors. These connectors were a new type developed by Lockheed and fabricated by Deutsch (Oceanside, Calif.). One of these was used in this dewar during the contract tests; the remaining three openings were sealed with blank plugs. Two similar electrical feedthroughs were utilized in the test tank located in the flight simulator. The dewar access cover flange, the window flanges, the vent-line flange, the connector flanges, and all mating fittings and plugs were provided with Conoseal glands to effectively seal the inner vessel during test operations.

The inner pressure vessel was designed using ASME unfired pressure vessel code criteria for a maximum operating pressure of 24.1 N/cm^2 (35 psia) or 13.8 N/cm^2 gage (20 psig). It was pneumatically proof-tested with gaseous nitrogen to 41.4 N/cm^2 gage (60 psig) applied in six cycles, prior to installation of the insulation system. The outer shell was initially assembled without the inner vessel, and vacuum-pumped to a pressure of 2.0×10^{-5} torr to check the structural integrity and low-vacuum sealing capability of the shell and seals. No problems were encountered in performing either the proof-test or the vacuum-pumpdown test. Figure 2-8 shows the inner and outer vessels after they were individually assembled and prepared for final mating. The inner vessel had already been insulated when this photograph was taken. The insulation used was aluminized/Mylar-Tissuglas blankets of the type developed under Contract NAS 8-20758. It performed during subsequent tests within 1 percent of its predicted design value.

Two 2.54-cm (1.0-in.) diam. fill and drain line connections were provided into the dewar that penetrate the inner vessel near the center of the lower hemispherical head. Multilayer-insulated, stainless-steel lines connect these penetrations through vapor

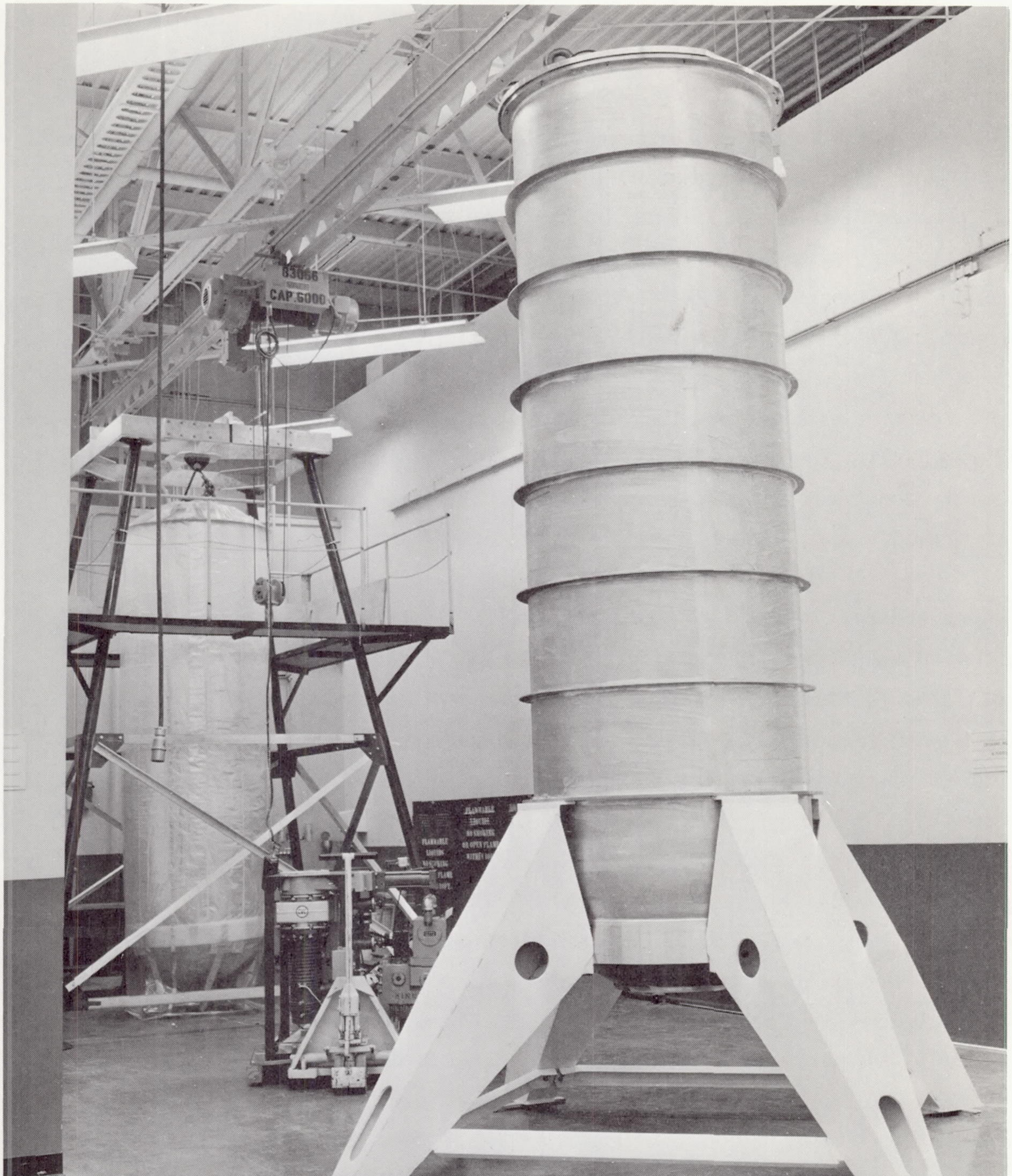


Fig. 2-8 Completed Inner Shell (Rear) and Outer Shell (Foreground) for Slush Storage Dewar

traps with bayonet fittings located near the intersection of the cylinder and the lower hemispherical head in the outer vessel shell. Cryogenic MS fittings and seals provide the aluminum-to-steel transition in these lines near the inner vessel penetration. A removable vacuum-jacketed, multilayer-insulated valve manifold that contains two pneumatically-operated, solenoid-actuated, remotely-controlled shutoff valves was provided. This manifold connects the dewar fill and drain lines to a single facility transfer line through a short flexible line section and bayonet fittings. One of the fill and drain lines protrudes into the bottom region of the inner vessel where it is perforated and covered with 30-mesh screen. This line provides the capability to withdraw liquid only from the tank, while the other line provides the capability to fill or drain liquid or slush.

A 0.64-cm (1/4-in.) diam. MS fitting and seal with a short weld-sealed line stub was installed in a third penetration of the inner vessel shell at the bottom. A corresponding 0.64-cm (1/4-in.) penetration and short capped line stub was installed through the lower, outer hemisphere. These penetrations were not used for slush storage, but can be used for later installation of a differential pressure gage for liquid storage if desired. A 15.2-cm (6-in.) diam. flanged penetration of the outer vessel shell was installed near the lower end of the cylinder. This penetration was provided to accommodate the dewar annulus vacuum-pumping system. A 10.2-cm (4.0-in.) diam. multilayer-insulated vent line was installed between the inner vessel cover and the upper, outer hemisphere. A guided bellows in this line accommodates thermal expansion and contraction of the inner vessel. The fitting that connects the upper end of this line to the outer hemisphere is sealed with coated metallic "V" seals. A tee was installed in the vent line just above the outer hemisphere. The horizontal leg of the tee provides for installation of a vacuum-pumping line when the dewar is modified to provide slush manufacturing capability at a later date. It was sealed with a blank plug for this test program. Above the tee fitting, the vent line reduces to a 5.1-cm (2-in.) diam., and extends through the roof of the A-frame enclosure to provide an independent dewar vent system. A pressure-actuated vent valve, burst disc assembly, two check valves, and a filter were installed in parallel branches of the vent line to control maximum inner vessel pressure. Two 5.1-cm (2-in.) diam. viewports and bosses for four electrical feedthrough connectors were also installed in the upper, outer hemispherical shell.

All external surfaces of the inner vessel, the fiberglass support struts and cone, and all inter-vessel plumbing lines were insulated with three overlapping multilayer insulation blankets. Total thickness of the combined multilayer blankets is approximately 2.54 cm (1.0 in.). The insulation can be seen after installation on the inner vessel in Fig. 2-8.

The multilayer blankets were prefabricated in oversized gores and polar caps for the inner vessel heads, and in oversized rectangular sections for the cylindrical shell. The oversized blanket sections were then trimmed to fit at close-tolerance butt joints during installation.

Each multilayer blanket section consists of seventeen 3.81×10^{-3} mm (0.15-mil) double-aluminized crinkled Mylar radiation shields separated by sixteen Tissuglas spacers. This insulation was the insulation developed under Contract NAS 8-20758 and rated in first place in the selective ranking system used in that contract. During prefabrication, all blanket sections were covered on both faces with Dacron mesh net to improve handling characteristics. The cylinder blanket sections were further reinforced in the vertical direction with Dacron ribbon, 1.27-cm (1/2-in.) wide, spaced on approximately 20.3-cm (8-in.) centers and sewn to the mesh net. The composite sections were then fastened together with molded Nylon button retains spaced approximately 15.2 cm (6 in.) on center. During installation, the cylinder blankets were suspended from the support cone at the top of the dewar using the Dacron ribbons. This fabrication technique was identical to that developed under Contract NAS 8-20758 to be used on the cylindrical section of the Modular Nuclear Vehicle. The lower gore and polar cap blankets were subsequently attached to the cylinder blankets with aluminized Mylar tape and Dacron thread. Adjacent cylinder and gore sections were attached at the butt joints using Teflon tabs and aluminized Mylar tape.

A vertical instrumentation probe was fabricated and installed in the storage dewar. The probe consists of a 5.1-cm (2-in.) diam. aluminum tube approximately 2.59 m (8 ft 6 in.) long, with two flat tapered aluminum extensions, each approximately 45.7-cm (1 ft 6 in.) long, welded to the tube at the ends. The probe was installed so

that its centerline is coincident with the vertical centerline of the dewar. It is supported at the top and bottom by a transverse aluminum structure that is bolted to standoffs welded inside the inner vessel shell.

Instrumentation provided with the probe includes (1) six visual level markers, (2) three carbon resistor liquid-level sensors, (3) seven gold plus 2.11 atomic percent cobalt versus copper thermocouples for slush-level measurements, (4) one platinum thermometer temperature sensor, and (5) one optical liquid-and slush-level sensor. The vertical elevation above or below the prime datum line which is located at the lower edge of the upper transverse support channel, the corresponding vertical elevation above the tank bottom, and the corresponding volume contained below that waterline elevation, are given in Table 2.1 for each of these instrumentation components.

Other supporting equipment, instrumentation, and controls provided and installed with the dewar include (1) a skid-mounted vacuum-pumping system that consists of a mechanical roughing pump, a 15.2-cm (6-in.) diffusion pump, cooling baffles, and automatic and manual operating valves, (2) a 15.2-cm (6-in.) diam. vacuum-pumping interconnect line and manual gate valve, (3) two cold cathode vacuum gages and a thermal vacuum gage, and (4) an inner vessel pressure gage, pressure transducer, vent-valve pressure switch, and an overpressure visual and audio warning system.

A 19-pin cryogenic electrical feedthrough connector developed by Lockheed and fabricated by Deutsch (subsection 3.7) was installed in the inner vessel cover to provide electrical power and instrumentation circuits for in-tank components. A standard bulkhead electrical feedthrough connector with an O-ring seal was installed in the upper, outer hemispherical head to accommodate the electrical wiring harness.

Table 2-1

ELEVATION AND VOLUME DATA FOR STORAGE DEWAR INTERNAL INSTRUMENTATION

Instrumentation (In Order of Position Above Bottom of Inner Vessel)	Elevation Above (+) or Below (-) Prime Datum at 289.1°K (520°R)		Elevation Above Bottom of Inner Vessel at 289.1°K (520°R)		Corresponding Volume Below Waterline at 13.9°K (25°R)		
	(cm)	(in.)	(cm)	(in.)	(Percent)	(m^3)	(ft^3)
Ref. Thermocouple, TC-0	-295.55	-116.36	20.68	8.14	2.000	6.086×10^{-2}	2.149
Temperature Sensor, RTB-1	-292.86	-115.30	23.37	9.20	2.500	7.610×10^{-2}	2.687
Visual Marker, VM-1	-243.13	-95.72	73.10	28.78	15.788	$4,805 \times 10^{-1}$	16.966
Thermocouple, TC-1	-217.50	-85.63	98.73	38.87	23.072	7.022×10^{-1}	24.794
Visual Marker, VM-2	-209.45	-82.46	106.78	42.04	25.365	7.719×10^{-1}	27.257
Thermocouple, TC-2	-204.80	-80.63	111.43	43.87	26.684	8.121×10^{-1}	28.675
Liquid-Level Sensor, LL-1	-175.56	-69.12	140.67	55.38	35.000	1.065	37.611
Visual Marker, VM-3	-165.00	-64.96	151.23	59.54	38.004	1.157	40.839
Visual Marker, VM-4	-120.55	-47.46	195.68	77.04	50.643	1.541	54.421
Visual Marker, VM-5	-76.10	-29.96	240.13	94.54	63.282	1.926	68.003
Liquid-Level Sensor, LL-2	-70.05	-27.58	246.18	96.62	65.000	1.978	69.850
Visual Marker, VM-6	-31.65	-12.46	284.58	112.04	75.921	2.310	81.585
Prime Datum Reference Line	0.0	0.0	316.23	124.50	84.920	2.584	91.255
Thermocouple, TC-3	-18.54	7.30	334.77	131.80	90.195	2.745	96.925
Optical Sensor, OS-1	-24.89	9.80	341.12	134.30	92.000	2.800	98.864
Thermocouple, TC-4	-31.24	12.30	347.47	136.80	93.721	2.852	100.714
Thermocouple, TC-5, and Liquid-Level Sensor LL-3	-36.14	14.23	352.37	138.73	95.00	2.891	102.088
Thermocouple, TC-6	-41.05	16.16	357.28	140.66	96.164	2.927	103.339

2.2 CONTROL AND INSTRUMENTATION BUILDING

All hazardous tests that are performed at the Cryogenic Vehicle Flight Simulator (described in subsection 2.1) can be monitored and controlled remotely from the control and instrumentation building (shown in Fig. 2-1). This building is located approximately 106.7 m (350 ft) from the cryogenic vacuum chamber. It houses the control consoles for the test pad and cryogen storage areas, the data-acquisition equipment, and the electrical power supplies, signal-conditioning, and distribution equipment. Control consoles located in the building include those used for (1) liquid and slush cryogen, pressurant gas, and purge gas handling, (2) the steam ejector and high-vacuum pumping systems, and (3) the vacuum chamber thermal environment simulation systems. The data-acquisition equipment located in the building includes the Dymec digital recording system, strip-chart recorders, and other data recorders and controls further described in Section 4.

The control and instrumentation building also contains closed-circuit television monitoring equipment, emergency control system equipment, fire detection and warning system equipment, and other communication and control equipment used to setup, checkout, and conduct cryogenic tests.

2.3 CRYOGEN AND PRESSURANT STORAGE AREA

As shown in Fig. 2-1, all cryogens, pressurant gases, and purge gases used in performing cryogenic tests at the test pad complex are stored in dewars and pressure containers located outside of the A-frame enclosure in the test pad area. Hydrogen and high-pressure storage containers are isolated from the test pad area by the blast wall and earth/sand revetment previously described in subsection 2.1. The major storage and distribution components are described in the following paragraphs.

2.3.1 Liquid Hydrogen Storage Dewar

The main liquid hydrogen storage dewar has a volume capacity of 49.2 m^3 (13,000 gal) and rests on a concrete foundation, with a 6.1-m by 15.2-m by 0.61-m (20 ft by 50 ft

by 2 ft) bed of crushed rock to act as a pebble bed flash heater in event of spillage. The dewar is of dual tank construction – an inner tank of stainless steel and an outer tank of carbon steel, with an annular space of 30.5 cm (12 in.) between them. The annular space is filled with Perlite insulating material and has a vacuum of less than 5 microns prior to loading with a cryogenic fluid.

The boiloff rate with liquid hydrogen in the dewar does not exceed 2 percent of its volume per day. Other specifics on the dewar are: diameter, 3.0 m (10 ft); length, 12.2-m (40 ft); and maximum working pressure, 69.0 N/cm^2 gage (100 psig). All fittings and valves are of stainless steel. A thermocouple vacuum gage monitors the vacuum in the annular space, and a carbon resistance probe measures the liquid level of the cryogen in the dewar.

A vent stack is provided in the dewar area for the safe disposal of boiloff gases. A GN_2 purge capability is available in the vent stack in case of stack fires. A 1.4-N/cm^2 gage (2 psig) pressure is maintained in the dewar ullage space by means of a check valve in the vent stack.

2.3.2 Liquid Hydrogen Vaporizer

The vaporizer is located below the LH_2 dewar and provides a means of pressurizing the dewar for the purpose of transferring either the liquid or gaseous cryogen from the storage area to the test pad. The equipment will provide an LH_2 flow at the pad of up to 7.57 m^3/min (2000 gpm) for a short duration, and a 1.89-m^3/min (500 gpm) steady flow rate. The unit consists of approximately 20.7 m (68 ft) of 10.2-cm (4-in.) tubing which, by environmental heating, changes the liquid cryogen to a gaseous cryogen. The liquid cryogen enters the vaporizer from the dewar and is returned from the vaporizer into the ullage space of the dewar. The vaporizer is controlled by a closed-loop electrical pneumatic control system.

2.3.3 Liquid Nitrogen Storage Dewar

The dewar has a volume capacity of 56.8 m^3 (15,000 gal), and is of dual tank construction. The inner tank is stainless steel, and the outer tank is carbon steel, with an annular space between them. The annular space is filled with Perlite insulating material and has a vacuum of less than 5 microns prior to loading with a cryogenic fluid. The maximum working pressure is 13.8 N/cm^2 gage (20 psig).

2.3.4 Cryogenic Fill Line

The facility has a vacuum-jacketed cryogenic fill line which is approximately 48.8 m (160 ft) long. This fill line extends from the LH_2 dewar to the test pad and is in an open horizontal "U" shape to allow for horizontal expansion and contraction of the entire line. The line is made of stainless steel with a 3-in. diam. hard inner line and a 12.7-cm (5-in.) diam. expansion-jointed outer line. The annular space contains static vacuum of less than 5 microns at ambient temperature. There are seven sections of the line individually vacuum-jacketed and containing a pumpdown port, a vacuum gage port, and a burst disphragm. In addition, a relief valve has been connected to the inner line and installed between each shutoff valve on the cryogenic transfer line to prevent an excessive pressure buildup from an entrapment of the cryogen.

2.3.5 Dump Line and Disposal Area

The dump line runs from the test hardware to an emergency disposal area of crushed rock. The line is made of 10.2-cm (4-in.) aluminum pipe and has expansion-jointed sections to allow for expansion and contraction. In addition, this line is also connected directly to the dewar in case it is necessary to dump the dewar for any reason.

The disposal of LH_2 requires that the gases escape at a distance high enough to avoid damage to the facility. For normal disposal of LH_2, a 18.3-m (60-ft) vent stack has been mounted on the dump line a short distance upstream of the disposal area to provide a means of discharging the hydrogen gas at a safe elevation.

2.3.6 Gaseous Nitrogen Supply

The area has two liquid nitrogen storage tanks, each having a compressor and high pressure receiver. The storage tanks have the capacity to supply 14,160 m^3 (500,000 standard ft^3) of nitrogen gas. The compressors deliver gaseous nitrogen at a rate of 1133 m^3 (40,000 standard ft^3) per hour to a high-pressure gas distribution system.

All the nitrogen gas passes through a 40-micron filter before entering the distribution system of the Cryogenic Vehicle Flight Simulator facility. The gaseous nitrogen supplied to the distribution systems may be stored in any of three 2206 N/cm^3 gage (3200-psig) gas storage spheres. Each sphere has a capacity of 1.1 m^3 (40 ft^3).

2.3.7 Gaseous Helium Supply

Gaseous helium is supplied from two high-pressure gas storage spheres. Each sphere has a capacity of 1.1 m^3 (40 ft^3), and can supply gaseous helium at 2206 N/cm^2 gage (3200 psi).

2.3.8 Gaseous Purge Systems

The purge systems in the facility have the capability of supplying gaseous hydrogen, helium, and nitrogen for purge use.

This system can take the cryogenic lines and test article from an atmospheric air condition to an inerted condition containing gaseous hydrogen. This is accomplished by first sweeping out the air by purging with gaseous nitrogen, then sweeping out the nitrogen by purging with gaseous hydrogen. An electrolytic hygrometer is employed for measuring water vapor in the purge gases. A water vapor content of 50 parts water vapor per million parts of gas must be achieved before the system is considered dry enough to avoid freezing up its control valves during the transfer of the liquid cryogenics during a test.

After a liquid hydrogen flow test, the test hardware and cryogenic lines are placed in a safe condition for post-test inspection by first purging the tank and cryogenic line with gaseous hydrogen until they reach a temperature above the freezing point of nitrogen. The gaseous hydrogen is then removed from the system by a means of a gaseous nitrogen purge.

When liquid hydrogen is stored in the dewar, a nitrogen purge is maintained on the dewar vent stack to prevent stack fires, and on all enclosures near the dewar which contain electrical equipment to prevent the collection of gaseous hydrogen in these confined areas. A nitrogen purge is also maintained on electrical equipment boxes near the pad when LH_2 is present in the pad area.

Check valves are used throughout the purge system to avoid accidentally mixing the purge gases and to prevent air from entering the purged volumes.

2.3.9 Rapid Pumpdown Capability

The Cryogenic Vehicle Flight Simulator is equipped with a combined steam ejector, roughing pump, and diffusion pump system, designed for performing ascent and space simulation tests in the vacuum chamber. This rapid pumpdown system was not used during the slush hydrogen test program.

2.3.10 Oxidizer Test Capability

An advanced oxidizer test capability (including the ability to flow large quantities of liquid oxygen, FLOX, or fluorine) is being installed in the Cryogenic Vehicle Flight Simulator. This capability was not used during the slush hydrogen test program.

Section 3
TEST APPARATUS DESCRIPTION

The apparatus that was developed to accomplish the contract test program is shown in Figs. 3-1 through 3-3. It consists of (1) a 105.4-cm (41.5-in.) diam. spherical test tank with an access cover, internal baffles, and other internal components, (2) upper and lower support frames and a tubular tripod tank support structure, (3) plumbing lines, valves, and fittings to accommodate slush fill, liquid recirculation, liquid fill and drain, pressurization, and venting operations, (4) multilayer insulation blankets attached to the tank and plumbing lines, and an insulated chamber completely enclosing plumbing and structural support penetrations, (5) a counterbalanced propellant weighing system, (6) submerged electrically-driven mechanical mixers, and (7) other instrumentation and controls for measurement of liquid level, temperatures, pressures, and flow rates.

3.1 TANK AND INTERNAL COMPONENTS

The 105.4-cm- (41.5-in.) diam. test tank and access cover are shown in Fig. 3-4. The tank assembly consists of two hemispherical half-shells, a Y-ring, a flange that mates with the 45.7-cm- (18-in.) diam. access cover, and a 3.8-cm- (1.5-in.) diam. plumbing penetration fitting. These components are joined together by circumferential butt welds. During assembly, the cover-mating flange and the plumbing penetration fitting were welded into the polar regions of the two hemispheres. Each was located so that its centerline was coincident with the polar axis of the tank. The two hemispheres were then welded to the Y-ring near the tank equator to complete the assembly.

A total of nine additional penetrations were provided into the tank through the access cover to accommodate plumbing and electrical feedthrough fittings. These include single penetrations of 13.653-cm- (5.375-in.) diam., 2.16-cm- (0.85-in.) diam., and

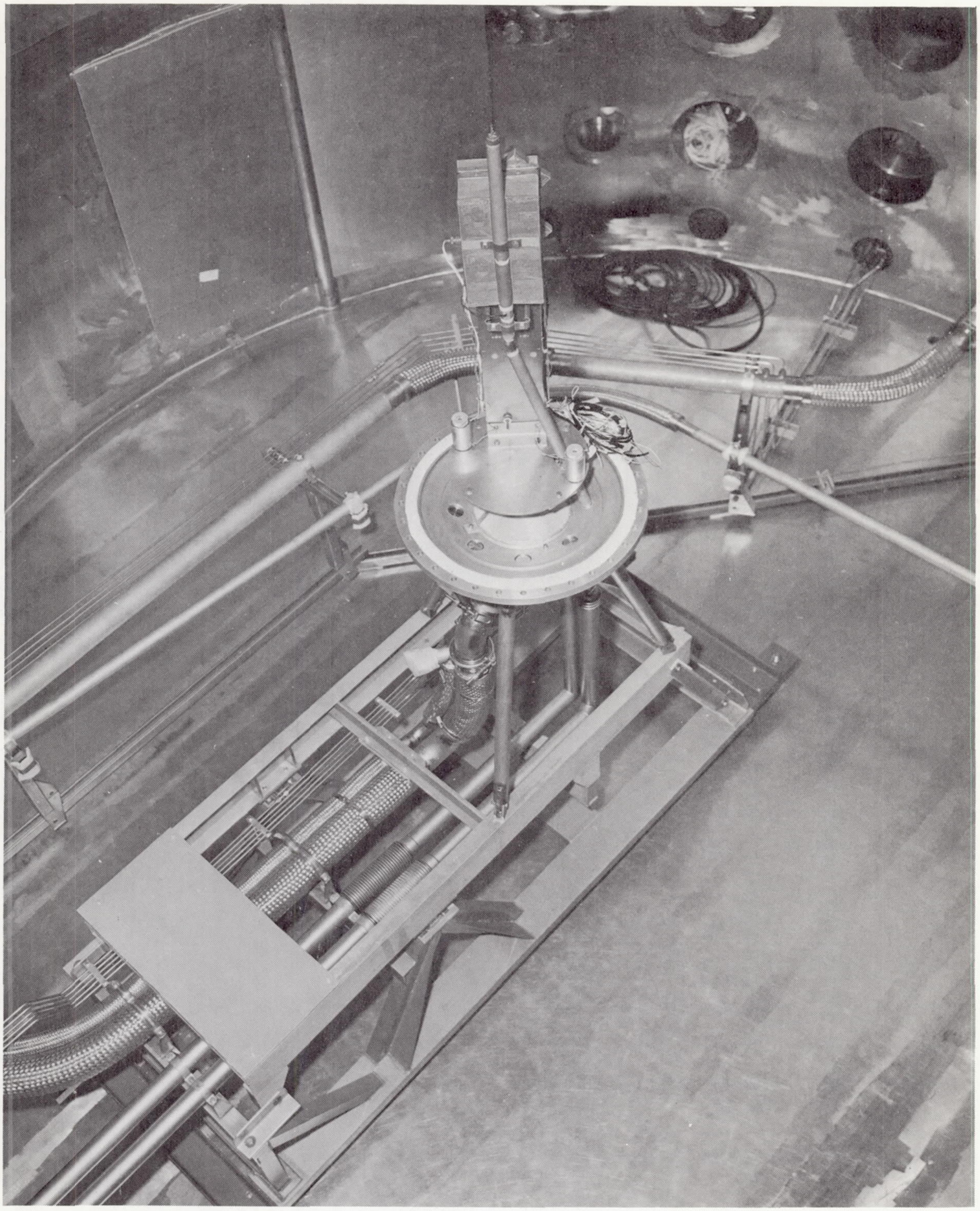


Fig. 3-1 Installation of Slush Hydrogen Test Apparatus in the Vacuum Chamber

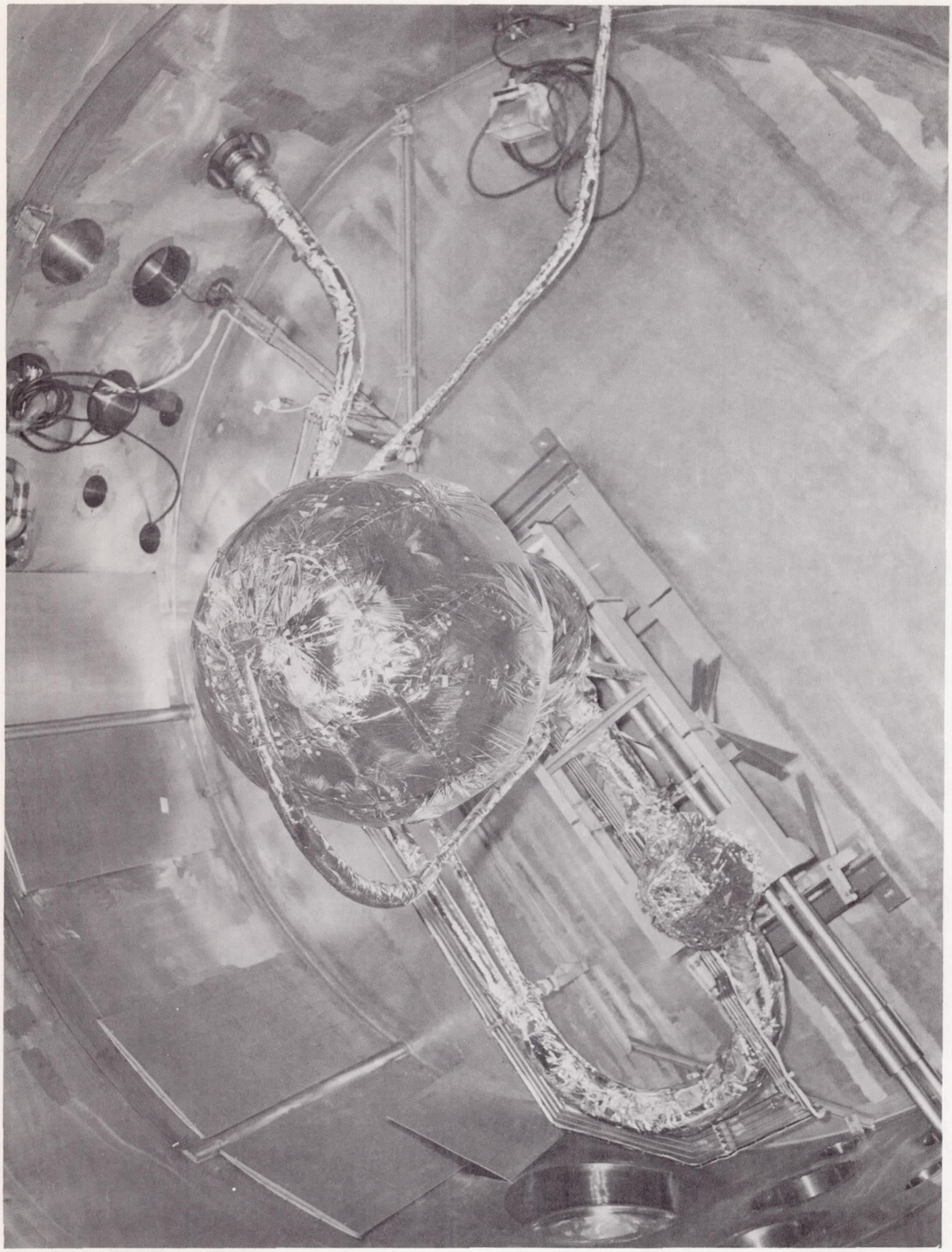


Fig. 3-2 Insulated Test Apparatus After Installation in the Vacuum Chamber

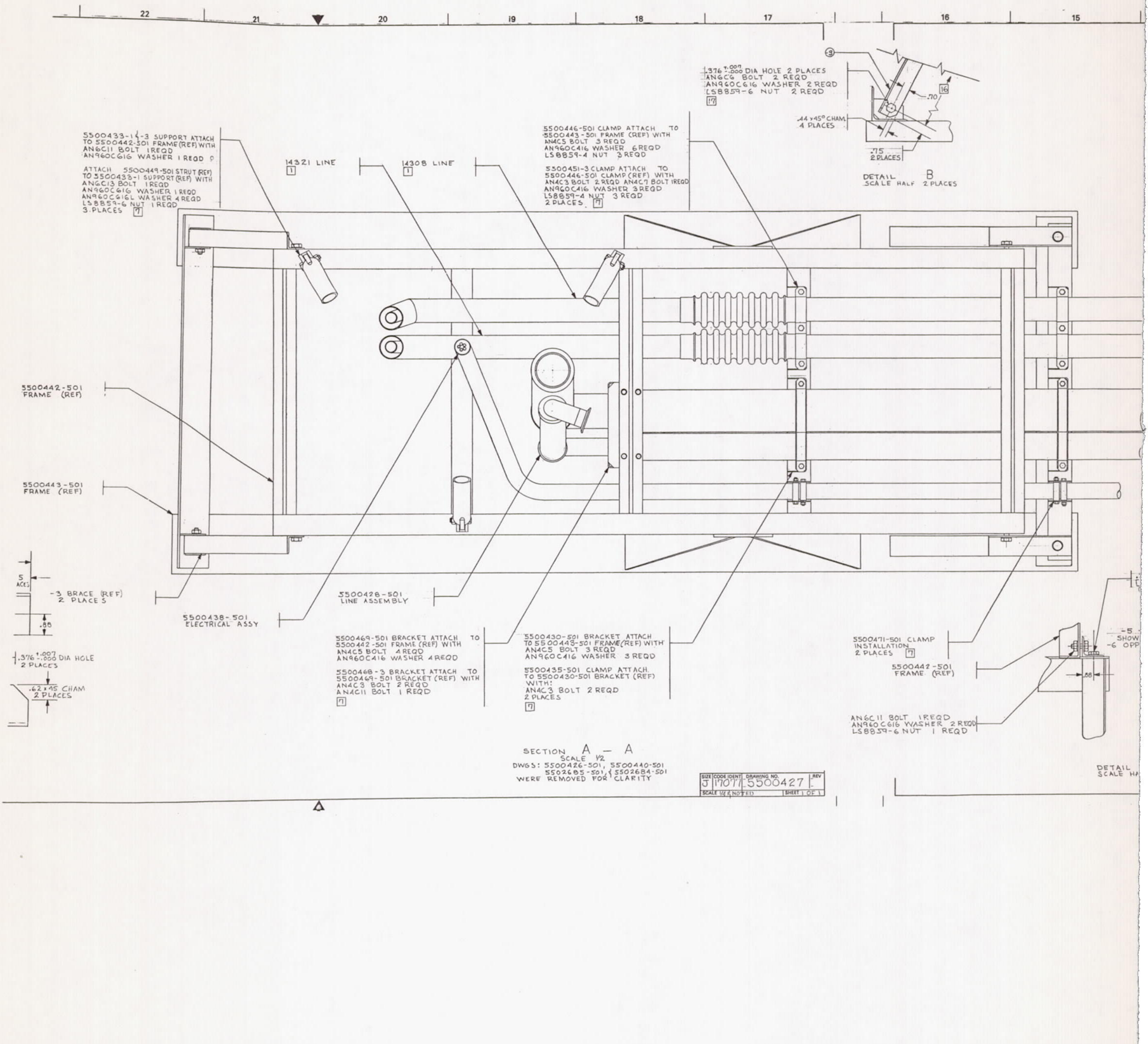
3.43-cm- (1.35-in.) diam., and six penetrations of 3.73-cm- (1.47-in.) diam. each. The 3.43-cm- (1.35-in.) diam. penetration and three of the six 3.73-cm- (1.47-in.) diam. penetrations were sealed with blank plugs and were not used during this contract test series. Conoseal glands were provided in the cover, the mating flange, and in all mating plugs and fittings to seal the tank for testing.

All tank-shell components were fabricated from 2219 aluminum alloy. Each hemisphere was power-spin formed from T351 plate, machined to a uniform 0.432-cm (0.170-in.) thickness, artificially aged to achieve mechanical properties similar to those of T87 plate, trimmed to the proper size, and then welded into the assembly. The Y-ring was machined from a T852 rolled-ring forging. The access cover, cover-mating flange, and the in-tank plumbing penetration fitting were machined from T851 plate.

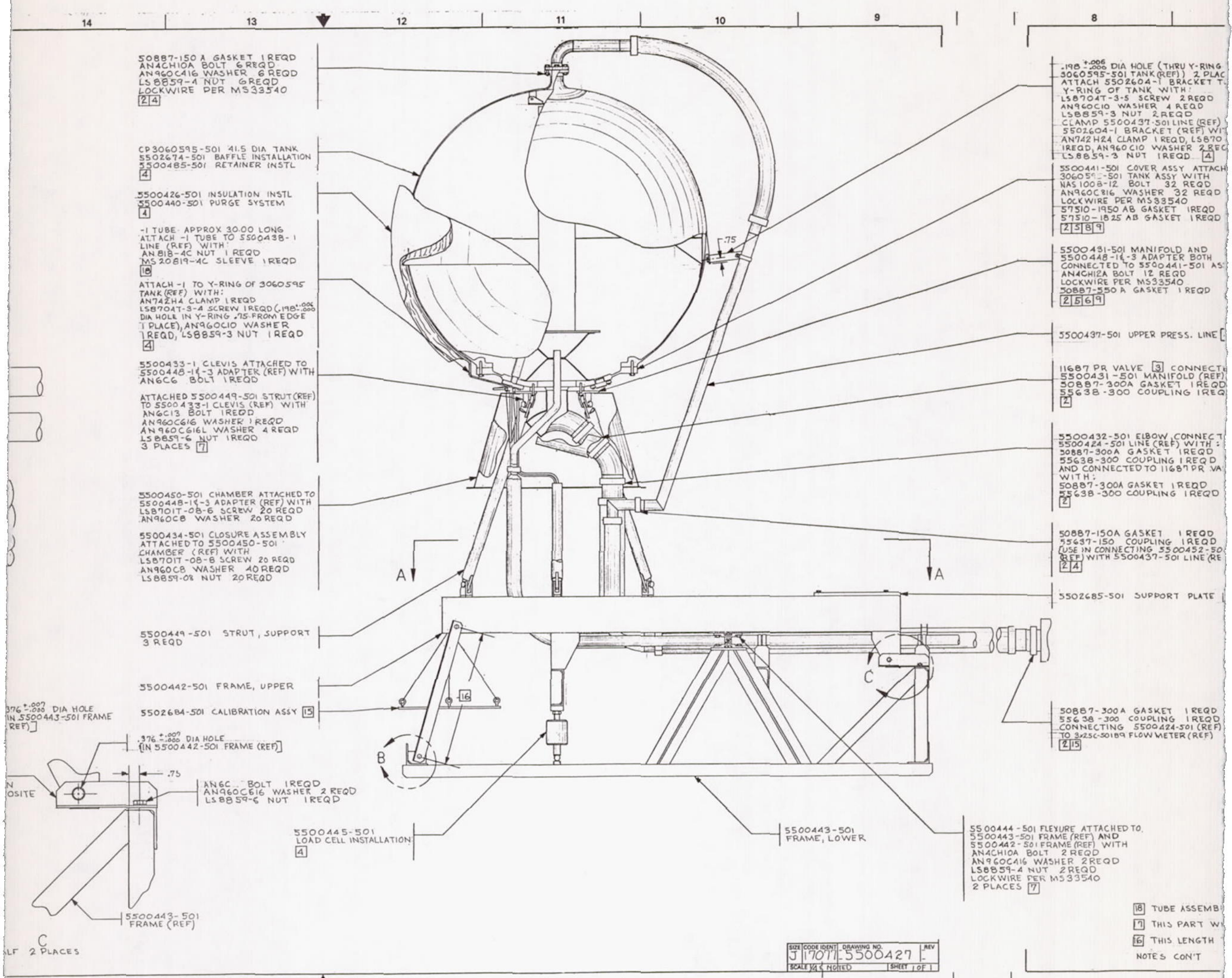
After the tank was assembled and welded, all weld areas were subjected to radiographic inspection. No discrepancies were found and no repairs were required. Structural integrity of the tank and cover was subsequently proven at ambient temperature by pneumatic proof-test to 68.95-N/cm^2 gage (100 psig). This pressure was applied in seven steps with pressure-relieving cycles between each step.

The test tank is oriented in the apparatus with the access cover at the bottom (see Figs. 3-1 through 3-3). It is supported by the structure below through a flange and fittings attached to the outside of the cover. Thus, the combined weight of the tank, the internal components, and the propellant contained in the tank is transmitted to the support structure through the cover, rather than through the Y-ring as would be the case for a flight vehicle tank. With this orientation, the interior surfaces of the cover, the lower tank plumbing fittings, the electrical feedthrough connectors, and all associated Conoseal glands are submerged when the tank is filled with liquid or slush hydrogen.

The internal components that are assembled inside the tank include (1) a circular aluminum stiffened ring, antislosh baffle, (2) a flat circular aluminum pressurant-diffuser baffle, (3) a conical 30-mesh aluminum solid-retention screen, (4) a flat



22
21
20
19
18
17
16
15
.376 +.007 -.000 DIA HOLE 2 PLACES
AN6C6 BOLT 2 REQD
AN960C616 WASHER 2 REQD
LS8859-6 NUT 2 REQD
17
3
16
.70
.44 x 45° CHAM. 4 PLACES
.75 2 PLACES
DETAIL B
SCALE HALF 2 PLACES
5500433-1 & -3 SUPPORT ATTACH TO 5500442-501 FRAME (REF) WITH
AN6C11 BOLT 1 REQD
AN960C616 WASHER 1 REQD
ATTACH 5500449-501 STRUT (REF) TO 5500433-1 SUPPORT (REF) WITH
AN6C13 BOLT 1 REQD
AN960C616 WASHER 1 REQD
AN960C616L WASHER 4 REQD
LS8859-6 NUT 1 REQD
3 PLACES 7
14321 LINE 1
14308 LINE 1
5500446-501 CLAMP ATTACH TO 5500443-501 FRAME (REF) WITH
AN4C5 BOLT 3 REQD
AN960C416 WASHER 6 REQD
LS8859-4 NUT 3 REQD
5500451-3 CLAMP ATTACH TO 5500446-501 CLAMP (REF) WITH
AN4C3 BOLT 2 REQD AN4C7 BOLT 1 REQD
AN960C416 WASHER 3 REQD
LS8859-4 NUT 3 REQD
2 PLACES 7
5500442-501 FRAME (REF)
5500443-501 FRAME (REF)
5 PLACES
-3 BRACE (REF) 2 PLACES
.88
.376 +.007 -.000 DIA HOLE 2 PLACES
.62 x 45 CHAM 2 PLACES
5500438-501 ELECTRICAL ASSY
5500428-501 LINE ASSEMBLY
5500469-501 BRACKET ATTACH TO 5500442-501 FRAME (REF) WITH
AN4C5 BOLT 4 REQD
AN960C416 WASHER 4 REQD
5500468-3 BRACKET ATTACH TO 5500469-501 BRACKET (REF) WITH
AN4C3 BOLT 2 REQD
AN4C11 BOLT 1 REQD
7
5500430-501 BRACKET ATTACH TO 5500443-501 FRAME (REF) WITH
AN4C5 BOLT 3 REQD
AN960C416 WASHER 3 REQD
5500435-501 CLAMP ATTACH TO 5500430-501 BRACKET (REF) WITH:
AN4C3 BOLT 2 REQD
2 PLACES
7
5500471-501 CLAMP INSTALLATION 2 PLACES 7
5500442-501 FRAME (REF)
AN6C11 BOLT 1 REQD
AN960C616 WASHER 2 REQD
LS8859-6 NUT 1 REQD
.88
-5 SHOWN
-6 OPP
DETAIL
SCALE HA
SECTION A — A
SCALE 1/2
DWGS: 5500426-501, 5500440-501
5502685-501, & 5502684-501
WERE REMOVED FOR CLARITY
SIZE J
CODE IDENT 17077
DRAWING NO. 5500427
REV
SCALE 1/2 & NOTED
SHEET 1 OF 1


14
13
12
11
10
9
8
50887-150 A GASKET 1 REQD
AN4CH10A BOLT 6 REQD
AN960C416 WASHER 6 REQD
LS8859-4 NUT 6 REQD
LOCKWIRE PER MS33540
2 4
CP3060595-501 41.5 DIA TANK
5502674-501 BAFFLE INSTALLATION
5500485-501 RETAINER INSTL
4
5500426-501 INSULATION INSTL
5500440-501 PURGE SYSTEM
4
-1 TUBE APPROX 30.00 LONG
ATTACH -1 TUBE TO 5500438-1
LINE (REF) WITH:
AN818-4C NUT 1 REQD
MS20819-4C SLEEVE 1 REQD
18
ATTACH -1 TO Y-RING OF 3060595
TANK (REF) WITH:
AN742H4 CLAMP 1 REQD
LS8704T-3-4 SCREW 1 REQD (.198 +.006 -.000
DIA HOLE IN Y-RING .75 FROM EDGE
1 PLACE), AN960C10 WASHER
1 REQD, LS8859-3 NUT 1 REQD
4
5500433-1 CLEVIS ATTACHED TO
5500448-1 -3 ADAPTER (REF) WITH
AN6C6 BOLT 1 REQD
ATTACHED 5500449-501 STRUT (REF)
TO 5500433-1 CLEVIS (REF) WITH
AN6C13 BOLT 1 REQD
AN960C616 WASHER 1 REQD
AN960C616L WASHER 4 REQD
LS8859-6 NUT 1 REQD
3 PLACES 7
5500450-501 CHAMBER ATTACHED TO
5500448-1 -3 ADAPTER (REF) WITH
LS8701T-08-6 SCREW 20 REQD
AN960C8 WASHER 20 REQD
5500434-501 CLOSURE ASSEMBLY
ATTACHED TO 5500450-501
CHAMBER (REF) WITH
LS8701T-08-8 SCREW 20 REQD
AN960C8 WASHER 40 REQD
LS8859-08 NUT 20 REQD
A
A
5500449-501 STRUT, SUPPORT
3 REQD
5500442-501 FRAME, UPPER
5502684-501 CALIBRATION ASSY 15
16
.376 +.007 -.000 DIA HOLE
IN 5500443-501 FRAME
(REF)
.376 +.007 -.000 DIA HOLE
IN 5500442-501 FRAME (REF)
.75
AN6C BOLT 1 REQD
AN960C616 WASHER 2 REQD
LS8859-6 NUT 1 REQD
B
C
5500445-501
LOAD CELL INSTALLATION
4
5500443-501
FRAME (REF)
C
2 PLACES
5500443-501
FRAME, LOWER
5500444-501 FLEXURE ATTACHED TO
5500443-501 FRAME (REF) AND
5500442-501 FRAME (REF) WITH
AN4CH10A BOLT 2 REQD
AN960C416 WASHER 2 REQD
LS8859-4 NUT 2 REQD
LOCKWIRE PER MS33540
2 PLACES 7
.75
.198 +.006 -.000 DIA HOLE (THRU Y-RING
3060595-501 TANK (REF)) 2 PLAC
ATTACH 5502604-1 BRACKET T
Y-RING OF TANK WITH:
LS8704T-3-5 SCREW 2 REQD
AN960C10 WASHER 4 REQD
LS8859-3 NUT 2 REQD
CLAMP 5500437-501 LINE (REF)
5502604-1 BRACKET (REF) WI
AN742H24 CLAMP 1 REQD, LS870
1 REQD, AN960C10 WASHER 2 REC
LS8859-3 NUT 1 REQD 4
5500441-501 COVER ASSY ATTACH
3060595-501 TANK ASSY WITH
NAS1008-12 BOLT 32 REQD
AN960C816 WASHER 32 REQD
LOCKWIRE PER MS33540
57510-1950 AB GASKET 1 REQD
57510-1825 AB GASKET 1 REQD
2 5 8 9
5500431-501 MANIFOLD AND
5500448-1 -3 ADAPTER BOTH
CONNECTED TO 5500441-501 AS
AN4CH12A BOLT 12 REQD
LOCKWIRE PER MS33540
50887-550 A GASKET 1 REQD
2 5 6 9
5500437-501 UPPER PRESS. LINE
11687 PR VALVE 3 CONNECT
5500431-501 MANIFOLD (REF)
50887-300A GASKET 1 REQD
55638-300 COUPLING 1 REQ
2
5500432-501 ELBOW, CONNECT
5500424-501 LINE (REF) WITH:
50887-300A GASKET 1 REQD
55638-300 COUPLING 1 REQD
AND CONNECTED TO 11687 PR VA
WITH:
50887-300A GASKET 1 REQD
55638-300 COUPLING 1 REQD
2
50887-150A GASKET 1 REQD
55637-150 COUPLING 1 REQD
(USE IN CONNECTING 5500452-50
(REF) WITH 5500437-501 LINE (RE
2 4
5502685-501 SUPPORT PLATE
50887-300A GASKET 1 REQD
55638-300 COUPLING 1 REQD
CONNECTING 5500424-501 (REF)
TO 3x25C-50189 FLOW METER (REF)
2 15
18 TUBE ASSEMB
17 THIS PART W
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NOTES CON'T
SIZE J
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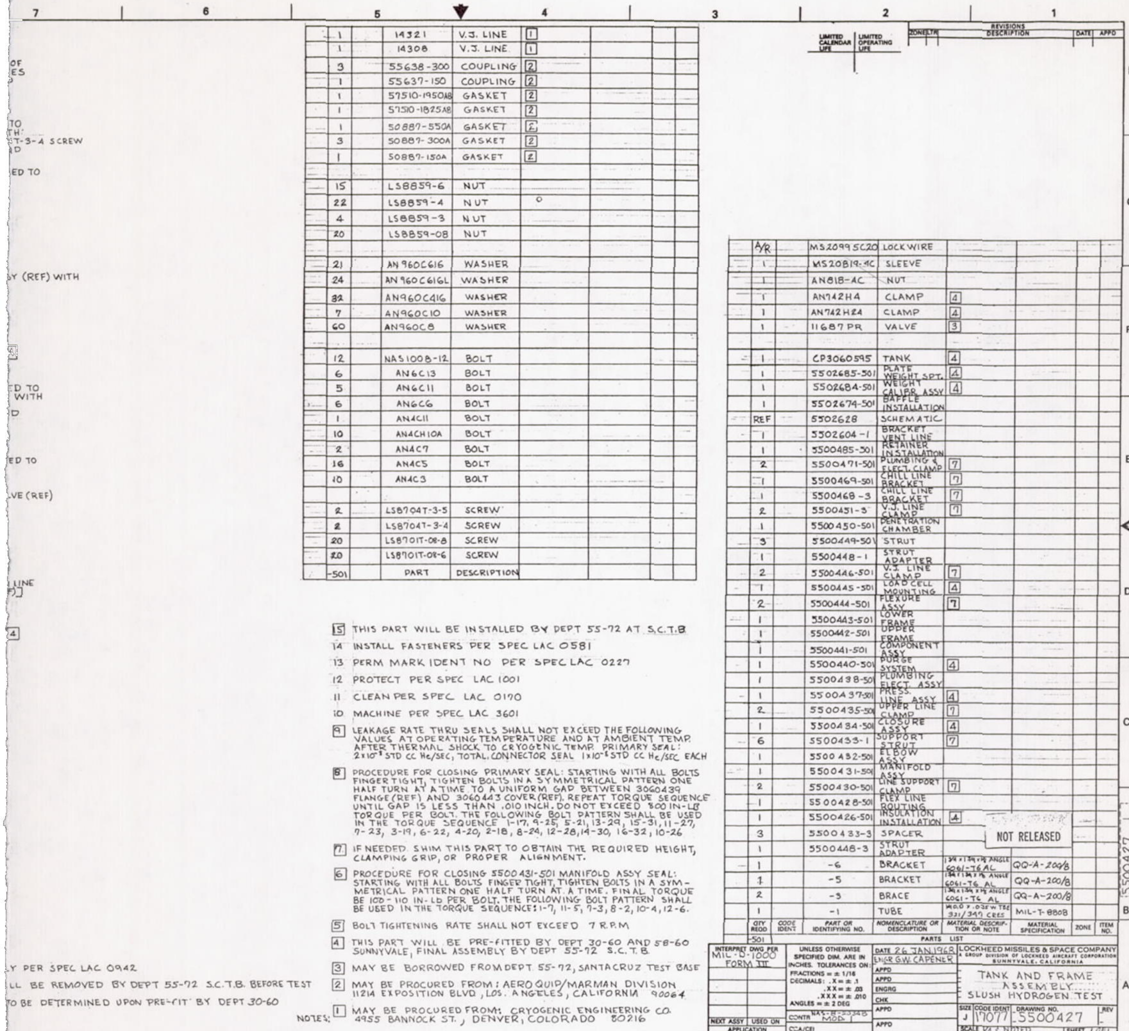

QTY	PART	DESCRIPTION	NOTE
1	14321	V.J. LINE	1
1	14308	V.J. LINE	1
3	55638-300	COUPLING	2
1	55637-150	COUPLING	2
1	57510-1950AB	GASKET	2
1	57510-1825AB	GASKET	2
1	50887-550A	GASKET	2
3	50887-300A	GASKET	2
1	50887-150A	GASKET	2
15	LS8859-6	NUT	
22	LS8859-4	NUT	
4	LS8859-3	NUT	
20	LS8859-08	NUT	
21	AN960C616	WASHER	
24	AN960C616L	WASHER	
32	AN960C416	WASHER	
7	AN960C10	WASHER	
60	AN960C8	WASHER	
12	NAS1008-12	BOLT	
6	AN6C13	BOLT	
5	AN6C11	BOLT	
6	AN6C6	BOLT	
1	AN4C11	BOLT	
10	AN4CH10A	BOLT	
2	AN4C7	BOLT	
16	AN4C5	BOLT	
10	AN4C3	BOLT	
2	LS8704T-3-5	SCREW	
2	LS8704T-3-4	SCREW	
20	LS8701T-08-8	SCREW	
20	LS8701T-08-6	SCREW	
-501	PART	DESCRIPTION	

QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO.
A/R		MS20995C20	LOCKWIRE				
1		MS20819-4C	SLEEVE				
1		AN818-4C	NUT				
1		AN742H4	CLAMP	4			
1		AN742H24	CLAMP	4			
1		11687PR	VALVE	3			
1		CP3060595	TANK	4			
1		5502685-501	PLATE WEIGHT SPT.	4			
1		5502684-501	WEIGHT CALIBR. ASSY	4			
1		5502674-501	BAFFLE INSTALLATION				
REF		5502628	SCHEMATIC				
1		5502604-1	BRACKET VENT LINE				
1		5500485-501	RETAINER INSTALLATION				
2		5500471-501	PLUMBING & ELECT. CLAMP	7			
1		5500469-501	CHILL LINE BRACKET	7			
1		5500468-3	CHILL LINE BRACKET	7			
2		5500451-3	V.J. LINE CLAMP	7			
1		5500450-501	PENETRATION CHAMBER				
3		5500449-501	STRUT				
1		5500448-1	STRUT ADAPTER				
2		5500446-501	V.J. LINE CLAMP	7			
1		5500445-501	LOAD CELL MOUNTING	4			
2		5500444-501	FLEXURE ASSY	7			
1		5500443-501	LOWER FRAME				
1		5500442-501	UPPER FRAME				
1		5500441-501	COMPONENT ASSY				
1		5500440-501	PURGE SYSTEM	4			
1		5500438-501	PLUMBING ELECT. ASSY				
1		5500437-501	PRESS. LINE ASSY	4			
2		5500435-501	UPPER LINE CLAMP	7			
1		5500434-501	CLOSURE ASSY	4			
6		5500433-1	SUPPORT STRUT	7			
1		5500432-501	ELBOW ASSY				
1		5500431-501	MANIFOLD ASSY				
2		5500430-501	LINE SUPPORT CLAMP	7			
1		5500428-501	FLEX LINE ROUTING				
1		5500426-501	INSULATION INSTALLATION	4			
3		5500433-3	SPACER				
1		5500448-3	STRUT ADAPTER				
1		-6	BRACKET	1 3/4 x 1 3/4 x 1/8 ANGLE 6061-T6 AL	QQ-A-200/8		
1		-5	BRACKET	1 3/4 x 1 3/4 x 1/8 ANGLE 6061-T6 AL	QQ-A-200/8		
2		-3	BRACE	1 3/4 x 1 3/4 x 1/8 ANGLE 6061-T6 AL	QQ-A-200/8		
1		-1	TUBE	1/4 O.D. x .035 W TBE 321/347 CRES	MIL-T-8808		
-501			PARTS LIST				

NOT RELEASED

INTERPRET DWG PER MIL-D-1000 FORM III

UNLESS OTHERWISE SPECIFIED DIM. ARE IN INCHES. TOLERANCES ON: FRACTIONS = ± 1/16 DECIMALS: .X = ± .1 .XX = ± .03 .XXX = ± .010 ANGLES = ± 2 DEG

CONTR NAS-8-23348 MOD 1

DATE 26 JAN 1968
ENGR G.W. CAPENER

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

TANK AND FRAME ASSEMBLY SLUSH HYDROGEN TEST

SIZE J CODE IDENT 17077 DRAWING NO. 5500427
SCALE 1/4 & NOTED SHEET 1 OF 1

NOTES:

15. THIS PART WILL BE INSTALLED BY DEPT 55-72 AT S.C.T.B
14. INSTALL FASTENERS PER SPEC LAC 0581
13. PERM MARK IDENT NO PER SPEC LAC 0227
12. PROTECT PER SPEC LAC 1001
11. CLEAN PER SPEC LAC 0170
10. MACHINE PER SPEC LAC 3601
9. LEAKAGE RATE THRU SEALS SHALL NOT EXCEED THE FOLLOWING VALUES AT OPERATING TEMPERATURE AND AT AMBIENT TEMP. AFTER THERMAL SHOCK TO CRYOGENIC TEMP. PRIMARY SEAL: 2×10^{-8} STD CC He/SEC, TOTAL. CONNECTOR SEAL 1×10^{-8} STD CC He/SEC EACH
8. PROCEDURE FOR CLOSING PRIMARY SEAL: STARTING WITH ALL BOLTS FINGER TIGHT, TIGHTEN BOLTS IN A SYMMETRICAL PATTERN ONE HALF TURN AT A TIME TO A UNIFORM GAP BETWEEN 3060439 FLANGE (REF) AND 3060443 COVER (REF). REPEAT TORQUE SEQUENCE UNTIL GAP IS LESS THAN .010 INCH. DO NOT EXCEED 800 IN-LB TORQUE PER BOLT. THE FOLLOWING BOLT PATTERN SHALL BE USED IN THE TORQUE SEQUENCE 1-17, 9-25, 5-21, 13-29, 15-31, 11-27, 7-23, 3-19, 6-22, 4-20, 2-18, 8-24, 12-28, 14-30, 16-32, 10-26
7. IF NEEDED SHIM THIS PART TO OBTAIN THE REQUIRED HEIGHT, CLAMPING GRIP, OR PROPER ALIGNMENT.
6. PROCEDURE FOR CLOSING 5500431-501 MANIFOLD ASSY SEAL: STARTING WITH ALL BOLTS FINGER TIGHT, TIGHTEN BOLTS IN A SYMMETRICAL PATTERN ONE HALF TURN AT A TIME. FINAL TORQUE BE 100-110 IN-LB PER BOLT. THE FOLLOWING BOLT PATTERN SHALL BE USED IN THE TORQUE SEQUENCE: 1-7, 11-5, 7-3, 8-2, 10-4, 12-6.
5. BOLT TIGHTENING RATE SHALL NOT EXCEED 7 R.P.M
4. THIS PART WILL BE PRE-FITTED BY DEPT 30-60 AND 58-60 SUNNYVALE, FINAL ASSEMBLY BY DEPT 55-72 S.C.T.B
3. MAY BE BORROWED FROM DEPT 55-72, SANTA CRUZ TEST BASE
2. MAY BE PROCURED FROM: AERO QUIP/MARMAN DIVISION 11214 EXPOSITION BLVD, LOS ANGELES, CALIFORNIA 90064
1. MAY BE PROCURED FROM: CRYOGENIC ENGINEERING CO. 4955 BANNOCK ST., DENVER, COLORADO 80216

…Y PER SPEC LAC 0942
…LL BE REMOVED BY DEPT 55-72 S.C.T.B. BEFORE TEST
…TO BE DETERMINED UPON PRE-FIT BY DEPT 30-60

Fig. 3-3 Test Apparatus Assembly Drawing

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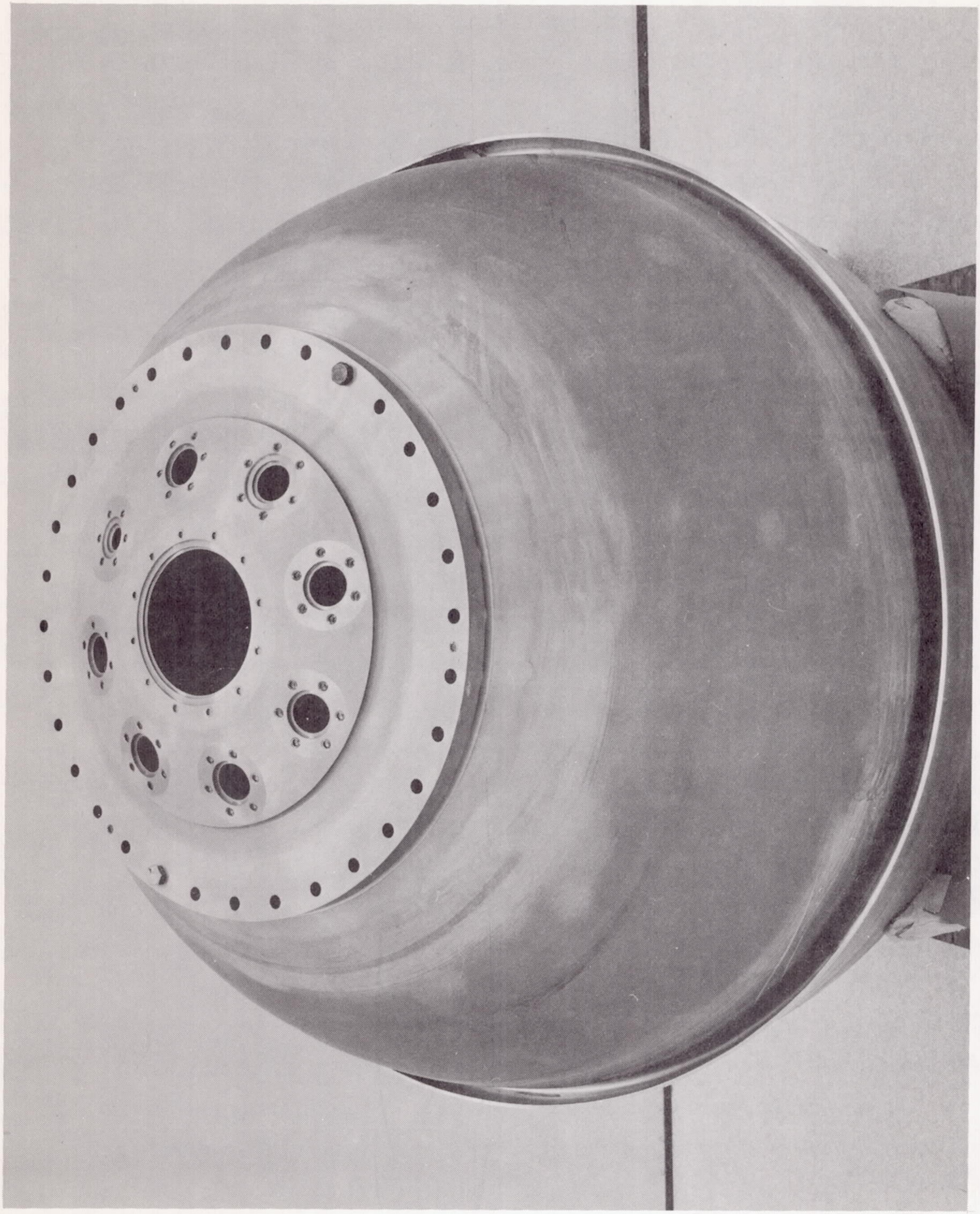


Fig. 3-4 105.4-cm (41.5-in.) Diameter Test Tank and Cover

circular aluminum slush-fill baffle, (5) a flat rectangular fiberglass instrumentation panel with two 30-mesh stainless steel screen instrumentation enclosures, and (6) a 1.91-cm (3/4-in.) diam. tubular fiberglass liquid-outflow recirculation line.

The antislosh baffle and the pressurant-diffuser baffle are supported inside the tank by 0.64-cm- (1/4-in.) diam. studs and extruded clips, respectively, which are welded to the tank shell. The slosh baffle is located near and is concentric with the tank equator. Its outer diameter is approximately 2.54-cm (1-in.) smaller than the inside diameter of the tank, so that an annular space approximately 1.27-cm (1/2-in.) wide exists between the baffle and the tank shell. This installation is shown in Fig. 3-5. The pressurant-diffuser baffle is located near the polar region of the tank in a plane parallel to that of the antislosh baffle. It is supported approximately 4.45 cm (1-3/4-in.) below the inside tank shell surface. The centerlines of this baffle and the pressurization-vent fitting are coincident with the tank polar axis.

The assembly that contains the remaining internal components is supported by the tank cover, as shown in Fig. 3-6. The conical solid-retention screen is located directly above and attached to the cover. Four formed aluminum brackets are bolted to the conical screen and, in turn, support the slush-fill baffle approximately 9.53 cm (3-3/4-in.) above the top of the screen, and approximately 17.78 cm (7-in.) above the tank cover. The slush-fill baffle is located in a plane parallel to those which contain the antislosh and pressurant-diffuser baffles. The centerlines of the solid-retention screen and the slush-fill baffle are coincident with the tank polar axis. The instrumentation panel extends vertically from the slush-fill baffle to the pressurant-diffuser baffle near the center of the tank. It is clamped to the liquid-recirculation line, which is coincident with the tank polar axis in the upper half of the tank. The upper end of the recirculation line was fitted through an opening in the center of the pressurant-diffuser baffle as the tank was mated to the cover during assembly. The internal components assembly is thus supported laterally at the top by the diffuser baffle. The recirculation line was sealed at its upper end to prevent outflow of ullage vapors during recirculation operations. Four symmetrically-located rectangular openings through

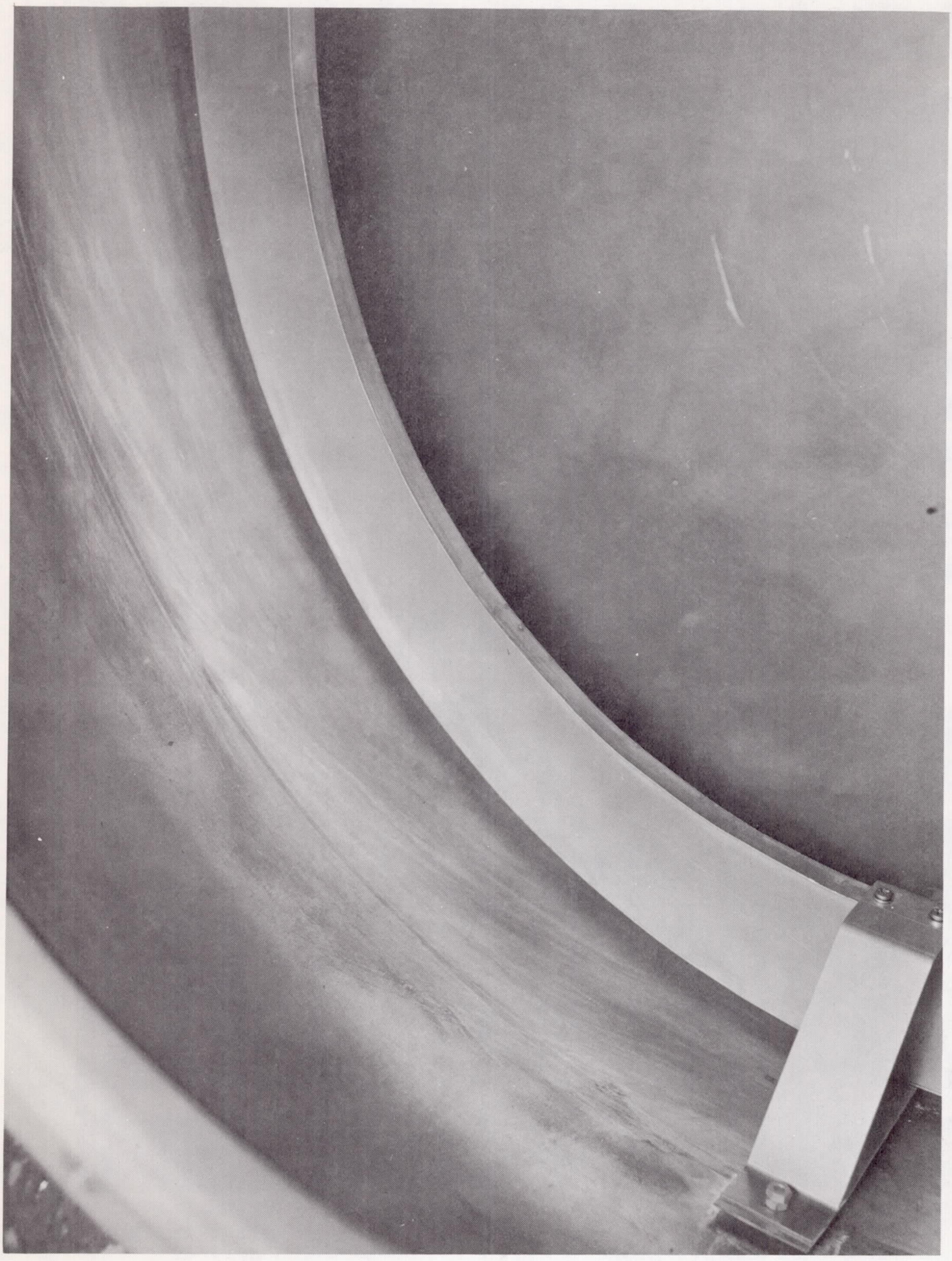


Fig. 3-5 Anti-Slosh Baffle Installation

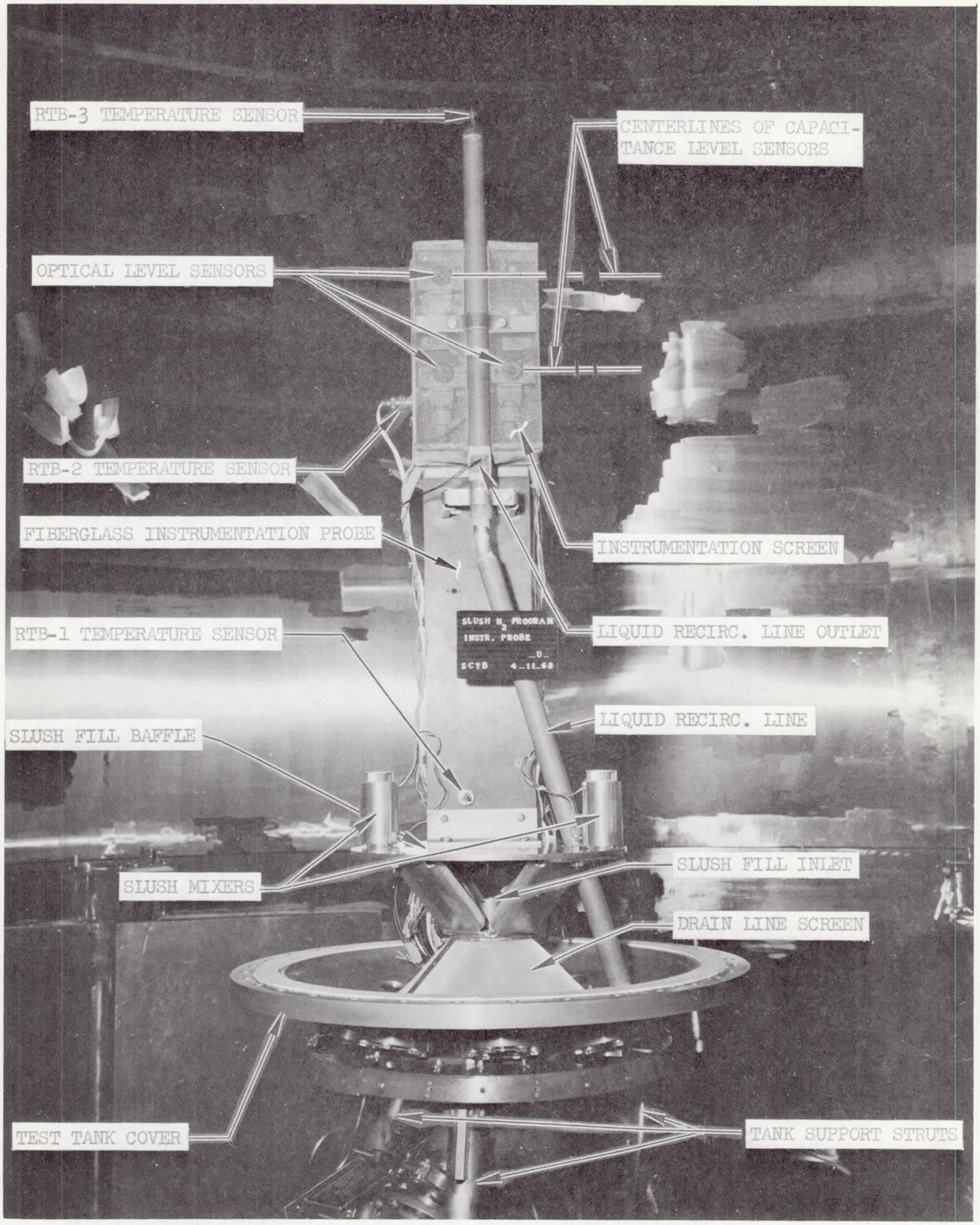


Fig. 3-6 Internal Components Assembled to the Tank Cover

the wall of this line provide for outflow of liquid from the tank. Each of these openings is approximately 1.12 by 1.27 cm (0.44 by 0.50-in.) in size. The upper edge of each opening is located approximately 11.43 cm (4-1/2-in.) below the nominal liquid-vapor interface position. It was determined by analysis that vapor pull-through could occur at the highest planned flow rate if the interface position were less than approximately 5.08-cm (2-in.) above the openings. Outflow of solid particles from the tank was prevented by 30-mesh screen which covers the openings.

3.2 SUPPORT STRUCTURE

The test tank and its supporting structure are shown in the photograph of Fig. 3-7 which was taken during prefit assembly operations. The tank is attached through fittings on the cover to the upper support frame by three 3.81-cm- (1.5-in.) diam. tubular stainless steel struts. The upper support frame is attached to and supported by the lower support frame through two stainless steel flexural supports and the load cell that was used to measure propellant weight (see Section 3.5). The load cell is located so that its principal axis is coincident with the vertical centerline (polar axis) of the test tank. The temporary angular restraining struts shown in the figure were removed during installation of the apparatus in the flight simulator to allow the tank and upper frame assembly to pivot about the horizontal axis of the flexural supports as the load cell is deflected under compressive loadings. Counterbalance weights were placed on the upper support frame plate (shown in the left foreground of the figure) to balance the empty weight of the tank, supporting structure, and plumbing so that the load cell was subjected to propellant weight only when the tank was filled.

3.3 PLUMBING COMPONENTS

Test apparatus plumbing components external to the test tank include: (1) two 2.54-cm- (1.0-in.) diam. vacuum-jacketed hard-line assemblies, (2) three nonjacketed flexline assemblies; two of 3.81-cm- (1.5-in.) diam. and one of 7.62-cm- (3.0-in.) diam., (3) a 7.62-cm- (3.0-in.) diam. Y-pattern manifold and mating shutoff valve, and

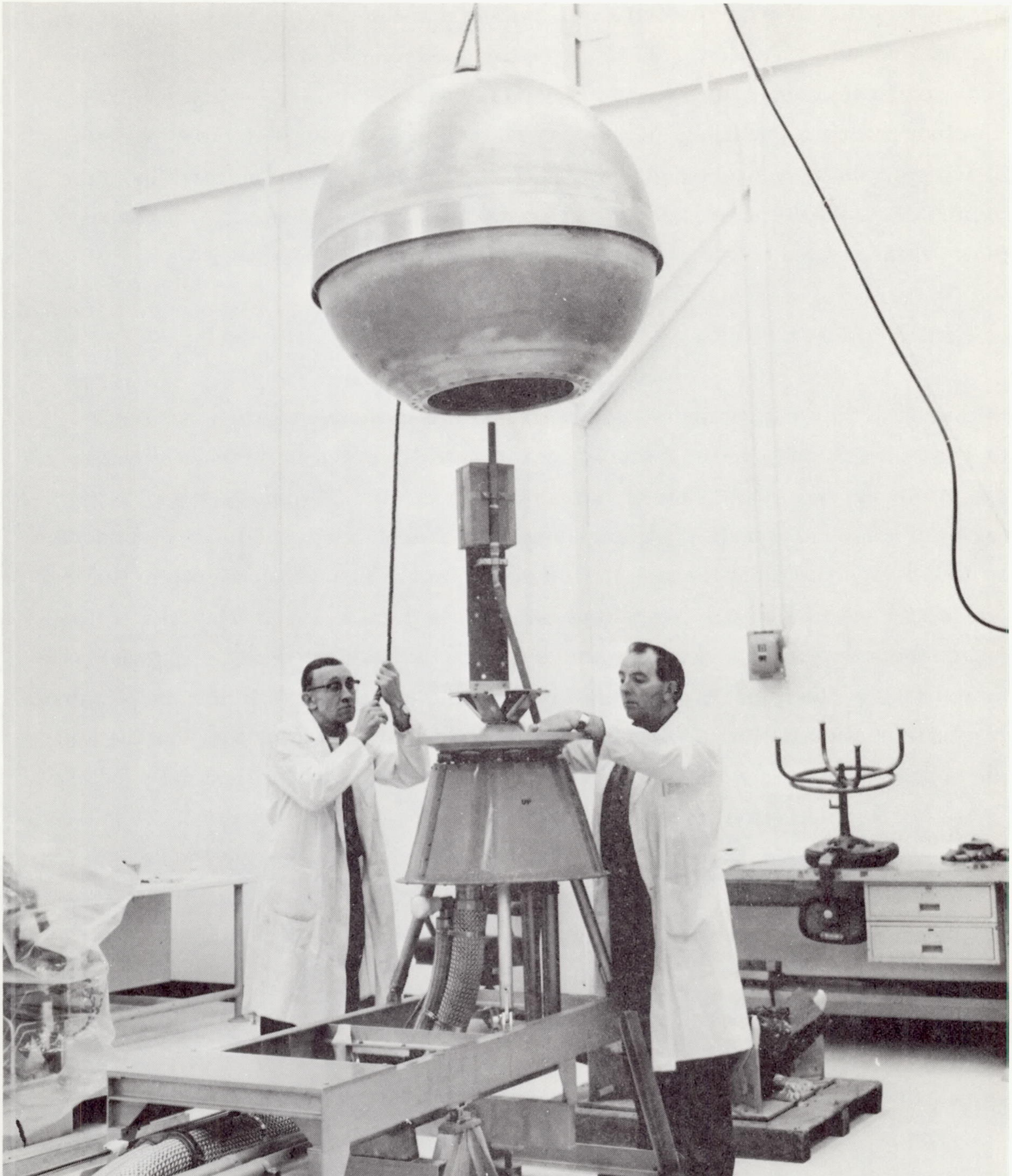


Fig. 3-7 Tank and Supporting Structure During Prefit Assembly

(4) five 0.64-cm- (1/4-in.) diam. lines. These components were all fabricated from stainless steel. Conoseal flanges were provided for connecting the 2.54-cm- (1.0-in.), 3.81-cm- (1.5-in.), and 7.62-cm- (3.0-in.) diam. lines and components to mating tank and line fittings, and (except for the 2.54-cm- (1.0-in.) diam. vacuum-jacketed lines) to mating vacuum-chamber pass-through fittings. Bayonet fittings were provided to mate the 2.54-cm- (1.0-in.) diam. vacuum-jacketed lines to corresponding facility lines just outside of the vacuum chamber passthrough flanges.

The general arrangement of the plumbing components with respect to the tank and apparatus can be seen in Figs. 3-1 through 3-3. A significant feature of the arrangement is that all plumbing lines (and the electrical wiring harness) are clamped to the support frames so that their centerlines pass through the flexural pivot axis. Thus, forces imposed on components of the apparatus due to chilldown of the lines, fluid pressure, and fluid inertia did not induce significant secondary forces on the load cell. Small secondary forces that were induced were reflected as errors in true propellant weight, as indicated by the load cell readings. Bellows sections were provided in each of the four larger diameter lines where they pass through the flexural pivot axis to minimize bending constraints that these lines impose on the loadcell as the system deflects under propellant weight (see Section 3.5 for further description of the weighing system).

The two vacuum-jacketed line sections accommodated slush flow into the tank and return flow of subcooled liquid from the tank during groundhold recirculation testing. Remotely operated shutoff valves were provided in mating facility lines outside the vacuum chamber to control the flow in both of these lines. Each of the lines is connected to the tank through short nonjacketed line sections located inside the insulated apparatus penetration chamber. The liquid return line penetrates the tank cover through the 2.16-cm- (0.85-in.) diam. opening in the cover, and mates with the fiberglass line section inside (see Section 3.1). The slush-fill line penetrates the tank inside of and concentric with one leg of the Y-pattern manifold, which is attached to the cover at the 13.653-cm- (5.375-in.) diam. opening in the center of the cover. The slush-fill line terminates approximately 15.24-cm (6-in.) inside the cover, just above the solid retention screen but below the flat circular slush-fill baffle (see Fig. 3-3).

The 7.62-cm- (3.0-in.) diam. flexline section is connected to the other leg of the Y-pattern manifold through the 7.62-cm- (3.0-in.) diam. remotely-operated shutoff valve. This valve was closed during recirculation operations, but was opened to (1) initially fill and chill the tank with atmospheric-saturated liquid hydrogen from the facility, and (2) drain subcooled liquid from the tank through the solid-retention screen to the facility drain system. The latter was required to drain the tank after chilldown (before filling it with slush), and later to simulate an engine firing during orbit test operations. The other end of the 7.62-cm- (3.0-in.) diam. flexline section is connected to the facility lines through a turbine flowmeter located just inside the vacuum chamber passthrough fitting (see Section 3.7).

The two 3.81-cm- (1.5-in.) diam. flexline sections are connected together to provide a common pressurization and vent line. This line is connected to the tank at the top through the 3.81-cm- (1.5-in.) diam. plumbing penetration fitting (see Fig. 3-3). It is clamped to the support frames so that its centerline passes through the flexural pivot axis. It is also clamped to (and insulated with) the 7.62-cm- (3.0-in.) diam. flexline for a distance of approximately 1.22-m (4-ft) in the region where both are clamped to the frame. This was designed to provide an effective heat exchanger to chill helium pressurant as it flowed from an ambient-temperature facility supply to the test tank ullage space. The common pressurization-vent line separates into two branches outside of the vacuum chamber passthrough fitting. One branch connects to a regulated helium pressurant supply; the other connects to the facility vent system through any one of several mass flowmeters.

Two of the five 0.64-cm- (1/4-in.) diam. plumbing lines connect the 7.62-cm- (3.0-in.) diam. shutoff valve to its pneumatic controller located outside the vacuum chamber. Two of those remaining connect an ambient helium purge gas supply from the facility to purge outlets located within the tank multilayer insulation system at the Y-ring and within the apparatus penetration chamber. During groundhold test operations, helium purge gas was bled through the apparatus insulation system to partially pressurize the surrounding vacuum chamber. The fifth 0.64-cm- (1/4-in.) diam. line connects a fitting on the 7.62-cm- (3.0-in.) diam. drain line (located just below the shutoff valve)

to the facility vent system. This line is coiled around the outer jackets of the 2.54-cm- (1.0-in.) diam. slush-fill and liquid-return lines where they penetrate the bottom of the apparatus penetration chamber. During groundhold test operations, liquid and/or gaseous hydrogen was vented through this 0.64-cm- (1/4-in.) diam. line to (1) intercept heat that would otherwise have been conducted into the test tank through the outer jackets of the 2.54-cm- (1.0-in.) diam. lines, and to (2) remove any hydrogen vapor that formed in the 7.62-cm- (3.0-in.) diam. drain line. The latter ensured that the drain line and the adjacent pressurization-vent line remained chilled to reduce penetration heat leaks, and that only liquid hydrogen was present to flow through the turbine flowmeter when the shutoff valve was opened to simulate an engine firing. All five 0.64-cm- (1/4-in.) diam. lines (and the electrical wiring harness) are clamped to the support frames as a bundle so that the centerline of the bundle passes through the flexural pivot axis.

3.4 INSULATION SYSTEM

All external surfaces of the test tank, apparatus penetration chamber, and plumbing lines were insulated with two overlapping multilayer insulation blankets. Total thickness of the combined multilayer blankets is approximately 0.64 cm (1/4 in.). In addition, the penetration chamber was filled with fiberglass batting material. The insulation system was installed after installation, checkout, and leak-testing of the apparatus, including plumbing and instrumentation, in the flight simulator at the test site. The insulation is shown in the photograph of Fig. 3-2.

The multilayer blankets were prefabricated in oversized gores and a polar cap for the tank, and in oversized cylindrical sections for the penetration chamber and the plumbing lines. The oversized blanket sections were then trimmed to fit at close-tolerance butt joints during installation.

Each multilayer blanket section consists of eight 3.81 by 10^{-3}-mm (0.15-mil) double-aluminized crinkled Mylar radiation shields separated by seven Tissuglas spacers. Each blanket section is held together by molded nylon button retainers spaced

approximately 15.24 cm (6 in.) on center. The inner blankets that were fitted directly to the tank, penetration chamber, and plumbing line surfaces, are held in place by Velcro strip fasteners. Overlapping outer blankets were attached by Teflon tabs and aluminized Mylar tape at the butt joints.

Fiberglass batting material was used to insulate around the strut supports and plumbing components within the apparatus penetration chamber. This material was provided to eliminate convective heat transfer through the helium vapor in the penetration chamber during simulated groundhold operations, and to act as a radiation barrier with the chamber evacuated during simulated space operations.

3.5 WEIGHING SYSTEM

The primary component of the propellant weighing system is a 0- to 45.36-kg (0- to 100-lb) loadcell. It is mounted vertically between the upper and lower support frames so that its principal axis is coincident with the polar axis of the tank as discussed in Section 3.2. Figure 3-8 is a photograph showing the installation. The loadcell is attached to a crossbeam of the upper frame, and rests on a tool-steel ball that is supported by a crossmember of the lower frame. The assembly consisting of the upper support frame, the tank support struts, and the tank with its internal components, plumbing, and insulation systems rotates about an axis through the two structural flexures that connect the upper and lower support frames as the loadcell deflects under compressive loadings. The total vertical deflection of the system including tank support struts, the crossbeam, the load cell with its attachment fittings, and support frame members was estimated by analysis to be approximately 2.159×10^{-2} mm (8.5×10^{-4} in.) under a full-scale loading of 45.36 kg (100 lb). This deflection results in an angular rotation of approximately 3.539×10^{-5} rad (7.3 sec) of arc about the pivot axis which is located 60.96 cm (24 in.) from the load cell axis.

As discussed previously, all plumbing and electrical lines were located so that their centerlines pass through the pivot axis. In addition, the slush-fill, liquid-return, liquid fill and drain, and the pressurization-vent lines were provided with flex sections

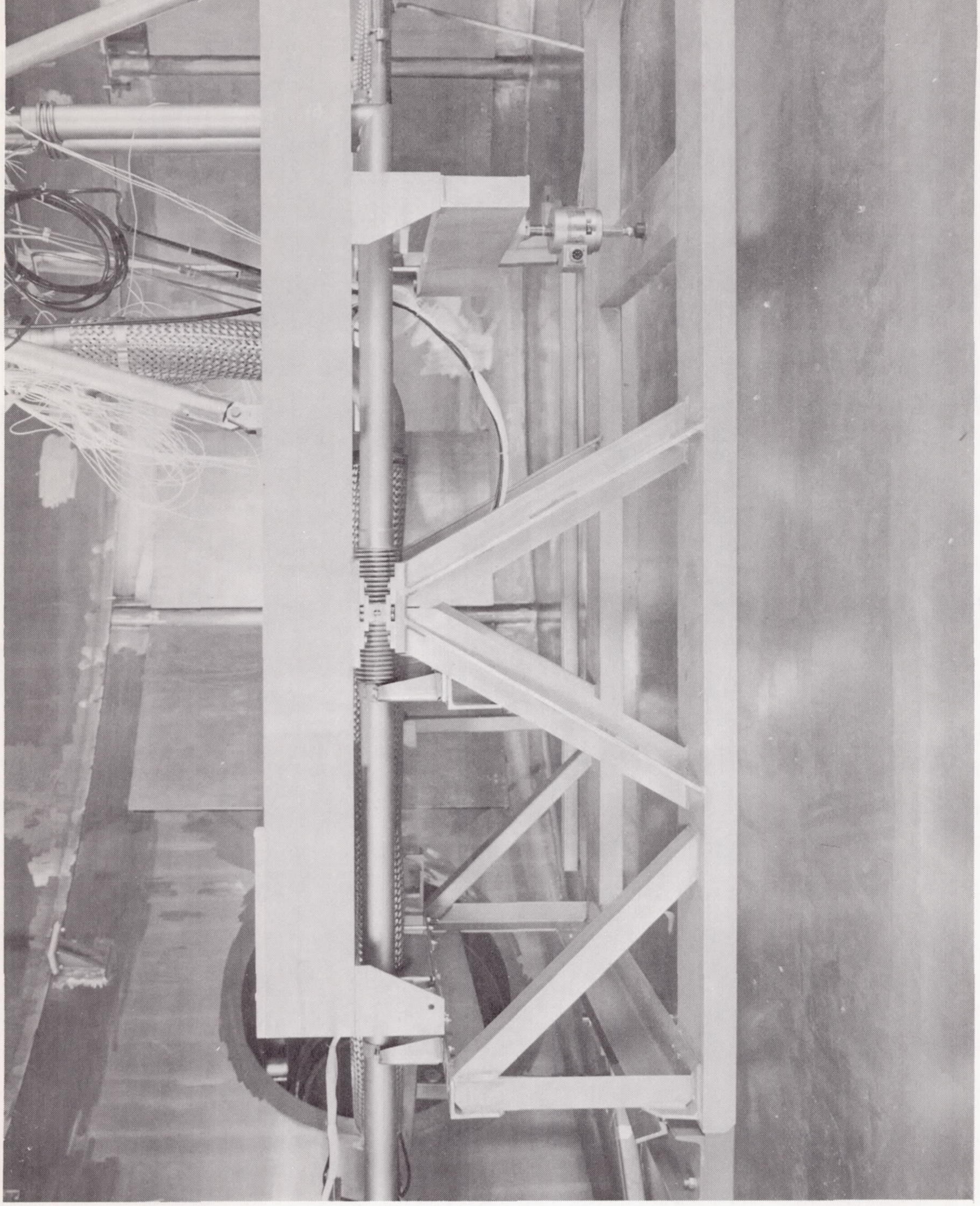


Fig. 3-8 Propellant Weighing System Installation

in the region of the pivot. The restoring moment that results from the 3.539×10^{-5} rad. (7.3 sec) of arc angular deflection of these lines is therefore extremely small, but does result in a slight decrease of the actual load imposed on the system. Errors in weighing due to this and other system effects were effectively reduced to negligible values, however, by performing complete system calibrations at both ambient and cryogenic temperatures using known standard weight increments.

A counterbalance weight of approximately 136-kg (300 lb) was positioned on the plate at the end of the upper support frame opposite the tank and load cell. This weight served to balance the tare weight of the system so that the load cell was nominally deflected by the weight of the propellant only. This resulted in more accurate weighing system measurements. The counterbalance weight was adjusted during calibration operations so that a slight preload existed on the load cell with the tank empty. This was done to ensure that the load cell support ball did not lift off of its contact during testing.

3.6 PROPELLANT MIXERS

Two electrically-driven centrifugal mixers developed by Globe Industries Incorporated were installed in the test tank to provide mechanical mixing of the slush during tank loading and groundhold recirculation testing, and to reduce stratification during all test sequences. These mixers were mounted directly on the slush-fill baffle and can be seen in Fig. 3-6. Figure 3-9 is a photograph taken prior to installation showing details of the mixer motors, impellers, and wiring.

The mixer impellers took suction vertically downward in the tank and expelled radially outward toward the tank wall in a horizontal plane. This flow pattern augmented the natural convection of the fluid upward along the tank wall as slush flowed into the bottom region of the tank below the slush-fill baffle and as liquid was withdrawn from the tank near the liquid-vapor interface.

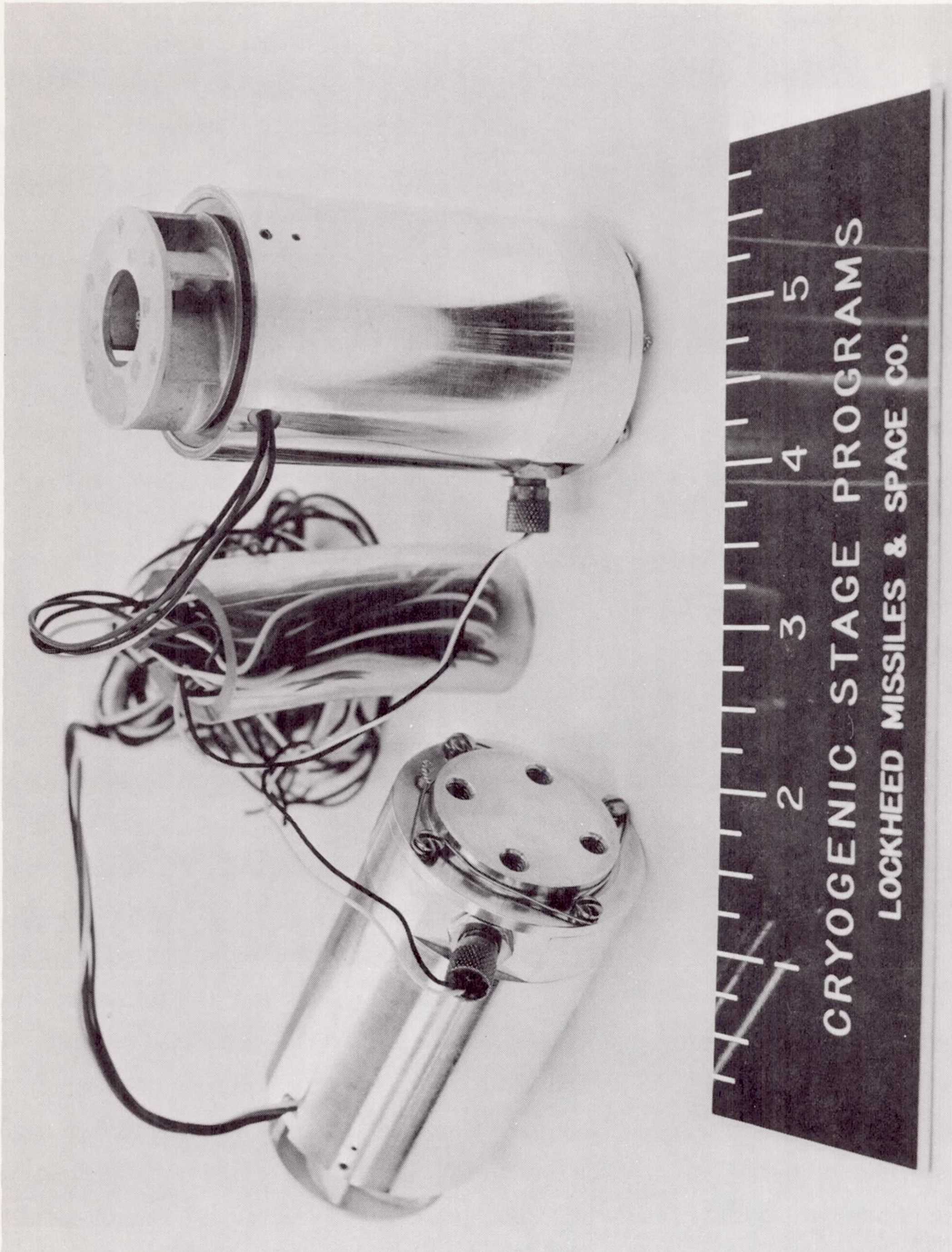


Fig. 3-9 Submersible Slush Mixers

3.7 OTHER INSTRUMENTATION AND CONTROLS

In addition to the load cell and the slush mixers, other instrumentation and controls provided with the 105.4-cm- (41.5-in.) diam. tank test apparatus included: (1) two capacitance level sensors, (2) three optical point level sensors, (3) four platinum thermometer temperature sensors, (4) four pressure transducers, (5) a turbine flowmeter, and (6) a thermal mass flowmeter. Of these, all of the level sensors and three of the temperature sensors were physically located inside the test tank. The vertical elevation above the prime datum line which is located at the bottom of the tank, and the corresponding volume contained below that waterline elevation, are given in Table 3-1 for all of the in-tank sensors as well as for other significant hardware reference locations.

A capacitance level-sensing system, partially shown in Fig. 3-10, was developed by Lockheed Palo Alto Research and Development Laboratory for this program. Two sensing elements, designated CC-1 and CC-2 (A sensor and B sensor, respectively, in the figure) were mounted at elevations in the tank (see Table 3-1) where volume control was desired. Each element provided a measurement of the liquid-vapor interface position, accurate to approximately ± 3.81 mm (± 0.15 in.) for a vertical distance of approximately 5.1 cm (2 in.) above and 5.1 cm (2 in.) below the nominal waterline control point at the centerline of the sensor (scribed line in the figure). A 30-mesh screened enclosure, Fig. 3-11, prevented the entry of solid particles between the sensor plates when installed in the tank. This ensured that the sensor measured the dielectric constant of only the relative liquid and vapor phases present to indicate the interface position. The electronic package shown in Fig. 3-10 is located outside the vacuum chamber and provided a "zero set" adjustment used to initially set the upper and lower limits of the output as read out on a meter at the control console in the blockhouse. This was done using liquid and gaseous hydrogen environments, and the optical point-level sensors, after installation and checkout of the system. The sensor output was used to drive the meter so that negative readings indicated discrete positions of the interface below the centerline, a zero reading indicated that the interface was at the centerline, and positive readings indicated discrete positions of the interface above the centerline. The widest part of the sensor, corresponding to the greatest sensitivity and accuracy of the system, is at the centerline.

Table 3-1

ELEVATION AND VOLUME DATA FOR IN-TANK INSTRUMENTATION AND OTHER HARDWARE REFERENCE LOCATIONS*

Instrumentation or Hardware Reference Location (In Order of Position Above Bottom of Tank)	Elevation Above Prime Datum at 289.1°K (520°R)		Corresponding Volume Below Waterline at 13.9°R (25°R)		
	(cm)	(in.)	(Percent)	(m^3)	(ft^3)
Prime Datum (Ref.)	0.0	(0.0)	0.0	0.0	(0.0)
Flat Surface on Inside Cover	1.57	(0.62)	0.07	4.248×10^{-4}	(0.015)
Cover Sealing Surface	6.17	(2.43)	0.99	6.032×10^{-3}	(0.213)
Top of Solid-Retention Screen	~9.53	(3.75)	~2.3	$\sim 1.399 \times 10^{-2}$	(0.494)
Slush-Fill Line Inlet	~13.97	(5.50)	~4.8	$\sim 2.917 \times 10^{-2}$	(1.030)
Slush-Fill Baffle	19.18	(7.55)	8.71	5.296×10^{-2}	(1.870)
Temperature Sensor, RTB-1	24.38	(9.60)	13.56	8.244×10^{-2}	(2.911)
Slush Mixer Impellers	~27.43	(10.80)	~16.8	$\sim 1.021 \times 10^{-1}$	(3.606)
Anti-Slosh Baffle	~52.71	(20.75)	~50.0	$\sim 3.040 \times 10^{-1}$	(10.734)
Centerline Liquid-Return Line Outlet	63.75	(25.10)	65.45	4.262×10^{-1}	(14.050)
Lower Edge of Capacitance Sensor, CC-1(A)	68.07	(26.80)	71.22	4.330×10^{-1}	(15.289)
Temperature Sensor, RTB-2	72.16	(28.41)	76.43	4.646×10^{-1}	(16.407)
Optical Sensor, OS-1	73.38	(28.89)	77.90	4.736×10^{-1}	(16.723)
Centerline Capacitance Sensor, CC-1(A)	73.63	(28.99)	78.20	4.754×10^{-1}	(16.787)
Optical Sensor, OS-2	73.89	(29.09)	78.50	4.772×10^{-1}	(16.852)
Upper Edge of Capacitance Sensor, CC-1(A)	78.84	(31.04)	84.12	5.114×10^{-1}	(18.058)
Lower Edge of Capacitance Sensor, CC-2(B)	80.16	(31.56)	85.52	5.119×10^{-1}	(18.359)
Optical Sensor, OS-3	85.29	(33.58)	90.47	5.500×10^{-1}	(19.421)
Centerline Capacitance Sensor, CC-2(B)	85.54	(33.68)	90.69	5.513×10^{-1}	(19.468)
Upper Edge of Capacitance Sensor, CC-2(B)	90.93	(35.80)	94.87	5.768×10^{-1}	(20.366)
Pressurant-Diffuser Baffle	~100.97	(39.75)	99.49	6.049×10^{-1}	(21.358)
Ullage Temperature Sensor, RTB-3	102.82	(40.48)	99.81	6.068×10^{-1}	(21.426)
Top of Tank	105.41	(41.50)	100.0	6.079×10^{-1}	(21.467)

*Assumes a perfect sphere of 105.4-cm (41.5-in.) diam. at 289.1°K (520°R) 105.1-cm- (41.380-in.) diam. at 13.9°K (25°R), and also assumes that the volume actually occupied by internal hardware components is equal to the volume contained by the liquid fill and drain line, the slush fill line, and the liquid return line between the tank and the weighing system pivot.

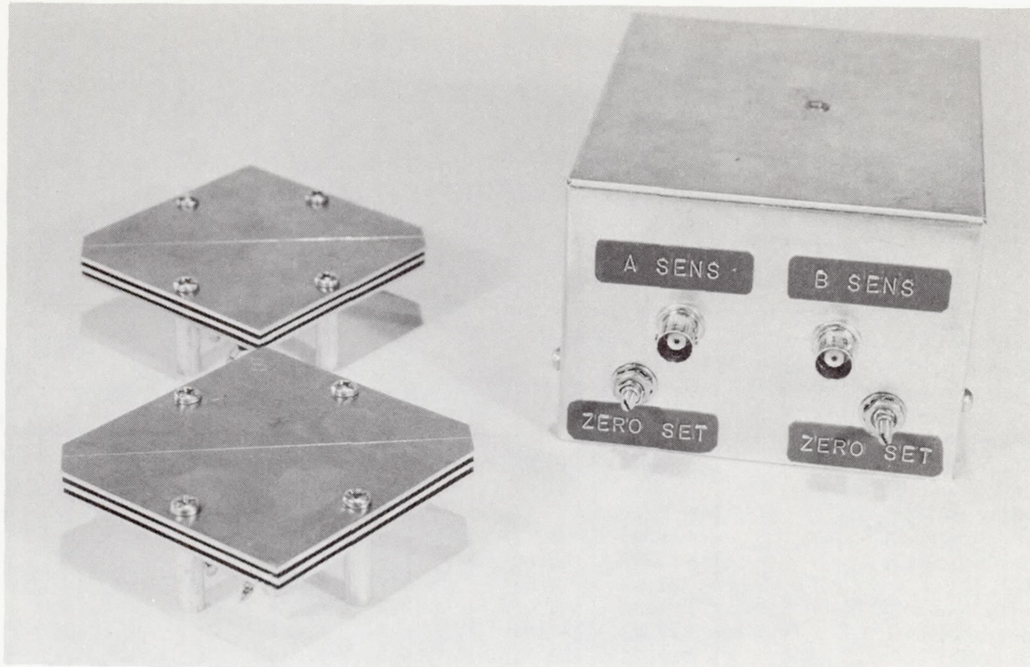


Fig. 3-10 Capacitance Level-Sensing System

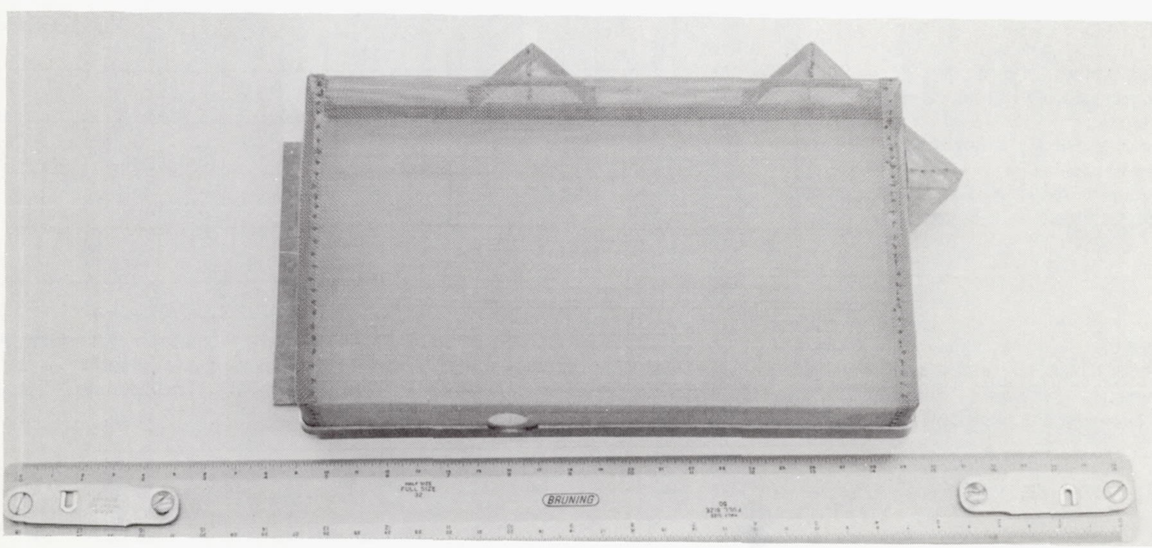


Fig. 3-11 Screen Enclosure for Test Tank Instrumentation

Two of the platinum thermometer temperature sensors (RTB-1 and RTB-2) were located to measure liquid or slush temperatures in the tank. A third (RTB-3) was located to measure pressurant or vented vapor temperatures. The fourth (RTB-4) was located in the 7.62-cm- (3.0-in.) diam. liquid fill and drain line just inside the flight simulator chamber passthrough.

Two pressure transducers (PG-1A and PG-1B) were located at the end of a short sensing line which tees off of the pressurization-vent line approximately 20.32-cm (8-in.) from the tank outlet. A third (PG-1C) was located in the facility vent line outside the vacuum chamber. The fourth (PG-2) was located near the RTB-4 temperature sensor in the 7.62-cm- (3.0-in.) diam. liquid fill and drain line.

The turbine flowmeter was also located in the 7.62-cm- (3.0-in.) diam. line, near RTB-4 and PG-2. These instruments were used to obtain flow data when liquid was withdrawn from the test tank through this line to simulate an engine firing in the orbit test sequence.

The thermal mass flowmeter was located in the facility vent line outside the flight simulator chamber. It was used to measure flow rates of hydrogen vapor vented from the tank during liquid hydrogen boiloff tests (see Section 6).

Three cryogenic feedthrough connectors were installed in the test tank cover to provide electrical power and instrumentation circuits for in-tank components. Two of these feedthrough connectors contain 19 standard solid pins each. Figure 3-12 is a photograph of one of these taken prior to installation. The third feedthrough connector contains two coaxial pins, used for the capacitance sensor circuits, and nine solid pins. All of these connectors were recently developed by the Deutsch Company under Lockheed Independent Development program funding.

Fig. 3-12 Cryogenic Electrical Feedthrough Connector

Section 4
DATA-ACQUISITION AND CONTROL SYSTEMS DESCRIPTION

The cryogenic test facility complex located at Santa Cruz Test Base, includes fairly extensive data-acquisition and controls equipment. The equipment that was integrated with the test setup for this contract includes: (1) a recording digital voltmeter, (2) a number of analog strip chart recorders, (3) various analog and digital display meters, (4) signal conditioning equipment, and (5) valve and equipment controls. Table 4.1 identifies the data acquisition equipment and channel of each test function with other related information. Figure 4-1 is a photograph of the interior of the instrumentation and control building and identifies the major elements that were used to perform contract tests.

4.1 RECORDING DIGITAL VOLTMETER

All primary data for this test program were gathered on the Dymec Model 2010J Recording Digital Voltmeter. This data-acquisition system has a total channel capacity of 400, of which approximately 30 channels were used on this program. The system operates in the following manner: Analog output voltage levels from instrumentation transducer functions located in the test system are scanned (sampled), converted from analog to digital format, and printed on paper tape. Overall common mode rejection is 124 db for an 0.1 sec sample period. System resolution is affected by the sample period: Table 4.2 summarizes the system resolution for three typical sample periods. Figure 4-2 shows the Dymec digital printer tape format. Overall system accuracy is ±1 digit of the last digit in the printout recording. Time is recorded on the paper tape from a digital system clock which provides standard time to all recording equipment within the instrumentation and control building.

Table 4-1

SLUSH HYDROGEN INSTRUMENTATION AND DATA-ACQUISITION EQUIPMENT

	SENSOR DESCRIPTION				DATA ACQUISITION						
					Dymec Dig. Ch. No.						
Setup Function	Code	Manufacturer	Model	S/N	Reading	Excit.	Stripchart Channel No.	Meter	Estimated System Accuracy		Remarks
Tank Internal Temp	RTB-1	Winsco	2448	140-70641	1	2	1-1	—	0.11°K	(0.2°R)	
Tank Internal Temp	RTB-2	Winsco	2448	146-70645	3	4	1-2	—	0.11°K	(0.2°R)	
Tank Ullage Temp	RTB-3	Rosmt	118L	A246	5	6	2-1	—	0.11°K	(0.2°R)	
Tank Fill Line Temp	RTB-4	Rosmt	118L	4074	7	8	2-2	—	0.11°K	(0.2°R)	
Tank Load Cell	LC-1	Trans. Inc	ML3-151	3059	9	10	3-1	Digital	45.36 g	(0.1 lb)	
Tank Pressure	PG1A	Statham	PA285	592793	11	12	4-1	Console		—	
Tank Pressure	PG1B	Statham	PA203	592333	13	14	4-2	—	0.34 N/cm^2	(0.5 psi)	
Tank Pressure	PG1C	Statham	PA285	5592795	15	16	—	—	0.34 N/cm^2	(0.5 psi)	
Tank Level	LLS-1	Bendix	GT103	250	17	-	—	—	2.54 mm	(0.1 in.)	
Tank Level	LLS-2	Bendix	GT103	151	18	-	—	—	2.54 mm	(0.1 in.)	
Tank Level	LLS-3	Bendix	GT103	149	19	-	—	—	2.54 mm	(0.1 in.)	
Fill and Drain Flow	FLW-1	Potter	-	-	20	-	6-1	—	220.8 cm^3/sec	(3.5 GPM)	
Fill Line Pressure	PG-2	CEC	0118	63695	21	22	—	—	0.34 N/cm^2	(0.5 psi)	
Storage Dwr Pressure	PG-3	Statham	PA285	S-007891	23	24	7-1	—	0.34 N/cm^2	(0.5 psi)	
Mfg. Dewar Pressure	PG-4	CEC	0003	S-801207	25	26	7-2	—	0.34 N/cm^2	(0.5 psi)	
Storage Dwr Ref Temp	RTB-5	Rosmt	118L	FS13	27	-	—	—	0.11°K	(0.2°R)	
Storage Dewar Level	LL4	—	-	-	-	-	8-1	—		—	Carbon Resistor
Storage Dewar Level	LL5	—	-	-	-	-	8-2	—		—	Carbon Resistor
Storage Dewar Level	LL6	—	-	-	-	-	5-2	—		—	Carbon Resistor
Storage Dewar Level	LL7	Bendix	GT103	-	-	-	—	Panel Lt.		—	Au-Co vs Cu T/C
Storage Dewar Int Temp	ST/C-1	—	-	-	-	-	—	Local Mtr		—	Au-Co vs Cu T/C
Storage Dewar Int Temp	ST/C-2	—	-	-	-	-	—	Local Mtr		—	Au-Co vs Cu T/C
Storage Dewar Int Temp	ST/C-3	—	-	-	-	-	—	Local Mtr		—	Au-Co vs Cu T/C
Storage Dewar Int Temp	ST/C-4	—	-	-	-	-	—	Local Mtr		—	Au-Co vs Cu T/C
Storage Dewar Int Temp	ST/C-5	—	-	-	-	-	—	Local Mtr		—	Au-Co vs Cu T/C
Storage Dewar Int Temp	ST/C-6	—	-	-	-	-	—	Local Mtr		—	Cu-Cr
Load Cell Temp	T/C	—	-	-	28	-	—	—		—	T/C
Vac. Chamber Pressure	—	Alphatron	-	-	-	-	—	Local Mtr			
Vac. Chamber Pressure	—	NRC	724	-	-	-	—	Console Mtr		—	
Tank Level	—	LMSC	-	-	-	-	—	Console Mtr		—	Capacitance
Tank Level	—	LMSC	-	-	-	-	—	Console Mtr		—	Capacitance
Mixer Current	—	—	-	-	-	-	—	Meter		—	
Mixer Volts	—	—	-	-	-	-	—	Meter		—	
Mixer Power Factor	—	—	-	-	-	-	—	Oscilloscope		—	
Mixer Speed	—	—	-	-	-	-	5-1	—		—	
Tank Vent Flow	FLW-2	Rosmt	-	-	29	-	—	—		—	

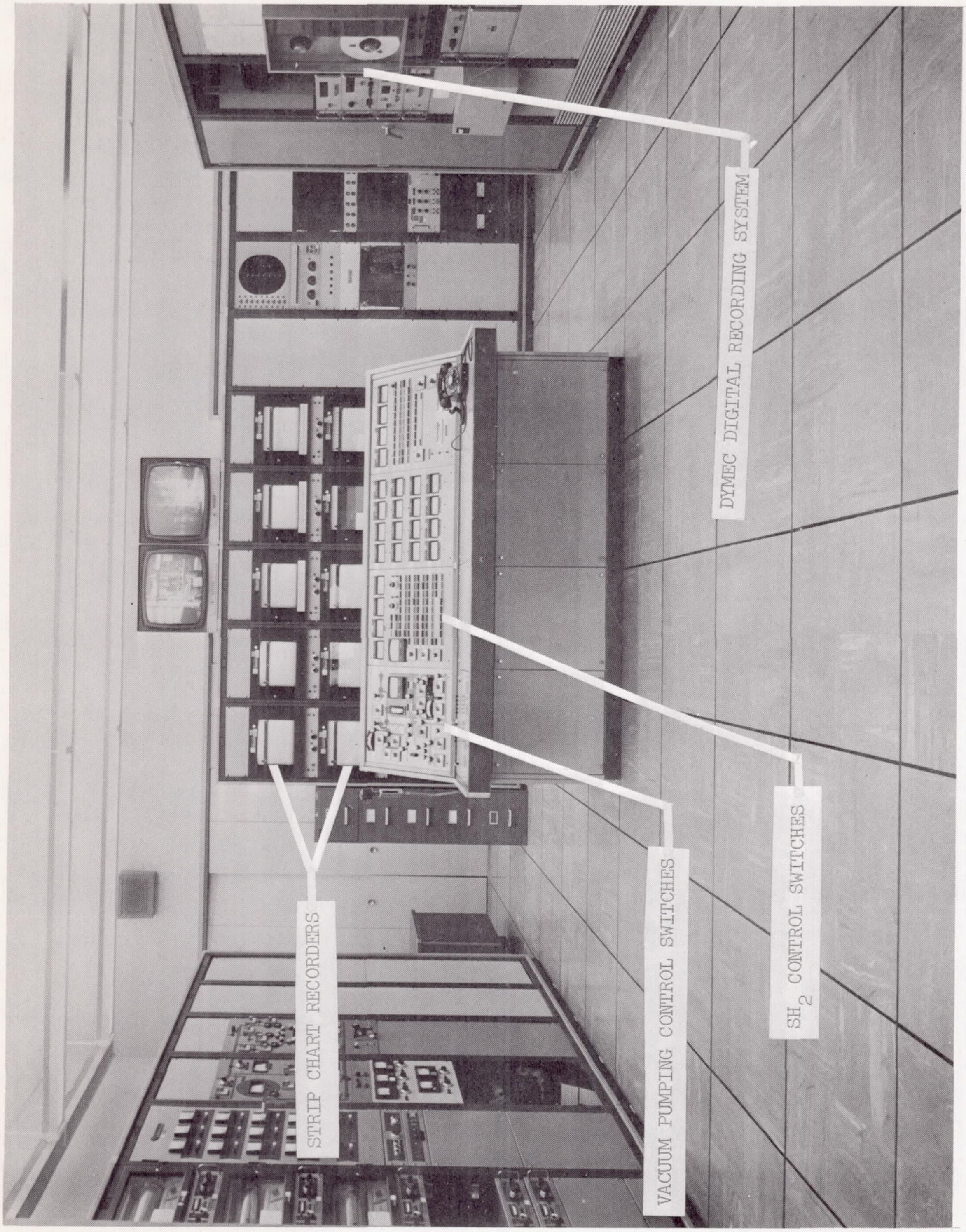


Fig. 4-1 Interior View of the Control and Instrumentation Building

Table 4-2

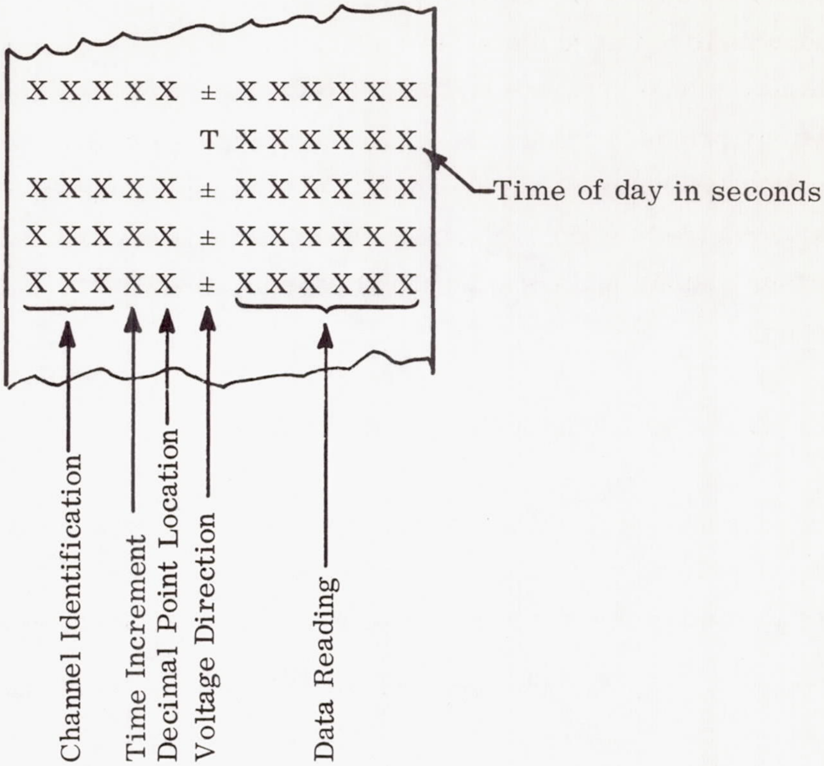
DYMEC SYSTEM RESOLUTION

Sample Period	Range	Full Scale Reading	Maximum Over Range Reading
1 sec	0.01	10.0000 mv	300.000 v
	0.1	100.000 mv	300.000 mv
	1.0	1000.00 mv	3000.00 mv
	10.0	10.0000 v	30.0000 v
	100.0	100.000	300.000 v
	1000.0	1000.00	—
0.1 sec	0.01	010.000 mv	0300.00 v
	0.1	0100.00 mv	0300.00 mv
	1.0	01.0000 v	03.0000 v
	10.0	010.000 v	030.000 v
	100.0	0100.00 v	0300.000 v
	1000.0	01000.0 v	—
0.01 sec	0.01	0010.00 mv	00300.0 v
	0.1	00100.0 mv	00300.0 mv
	1.0	001.000 v	003.000 v
	10.0	0010.00 v	0030.00 v
	100.0	00100.0 v	00300.0 v
	1000.0	001000.0 v	—

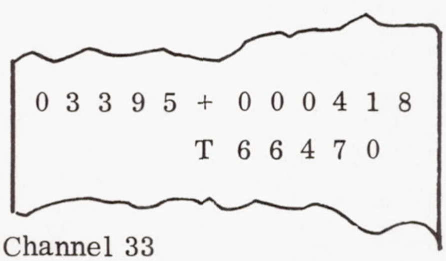
4.2 ANALOG STRIP CHART RECORDERS

Certain instrumentation functions were selected for visual, analog display on Mosley Model 7100B Stripchart Records. Sixteen of these stripcharts are located in the control and instrumentation building in locations of good visual access for the test conductor at the control console. These Mosley recorders incorporate electric writing and have a slewing speed of 1/2 sec full scale. Twelve chart speeds from 2.54 cm/hr to 2.54 mm/sec (1 in./hr to 0.1 in./sec) can be selected from a front panel-mounted selector switch. Each writing element is independently operating from plug-in span modules with sixteen front panel selected spans from 1 mv to 100v full scale. Inputs are floating, have high common mode rejection, and present a load resistance of 1 megohm at null on all calibrated spans. Accuracy of recorder is 0.2 percent of full scale with a linearity of 0.1 percent of full scale.

Column Identification:



Example:



- Function on Channel 33
- Data taken at 66479 sec after midnight
- Transducer output plus 0.00418 v

Fig. 4-2 Digital Printer Tape Format

4.3 ANALOG AND DIGITAL DISPLAY METERS

Various instrumentation functions used for test operations controls are displayed on standard ammeters, wattmeters, and digital voltmeters. Hand recorded data from these meters was gathered for mixer information. Loadcell output was continuously displayed on a separate stripchart recorder in addition to the Dymec record. This display provided the test conductor with the weight data required to control the inflow and outflow rates during slush quality upgrading operations. Liquid-level (volume) data required for control during these operations was obtained from the capacitance sensor display meters and optical sensor output lights that are mounted on the control console.

4.4 SIGNAL CONDITIONING EQUIPMENT

Instrumentation transducer outputs for this program were low level and power supplies and amplifiers were required for signal conditioning. These equipment components are located in the instrumentation and control building and include:

210 channels – B&F PC 2400 series power supplies
54 channels – Endevco 4401 power supplies
54 channels – Kintel 111, 112, 114 dc amplifiers
20 channels – Dynamics 7504 dc amplifiers
100 channels – Research, Inc., 338.8°K (150°F) T/C reference
200 channels – LMSC Liquid Nitrogen T/C reference

4.5 VALVE AND EQUIPMENT CONTROLS

During contract test operations, all equipment was controlled from the instrumentation and control building. The slush hydrogen, liquid hydrogen, purge valves, and vacuum pumping equipment are operated by 28 vdc signals. The electrical power is controlled by switches located on the control console identified in the Fig. 4-1 photograph. On the left-hand section of the control console are the vacuum pumping control switches

and on the center section are the hydrogen and purge valve control switches. Figure 4-3 is a close-up photograph of the slush hydrogen control switches mounted on the control console.

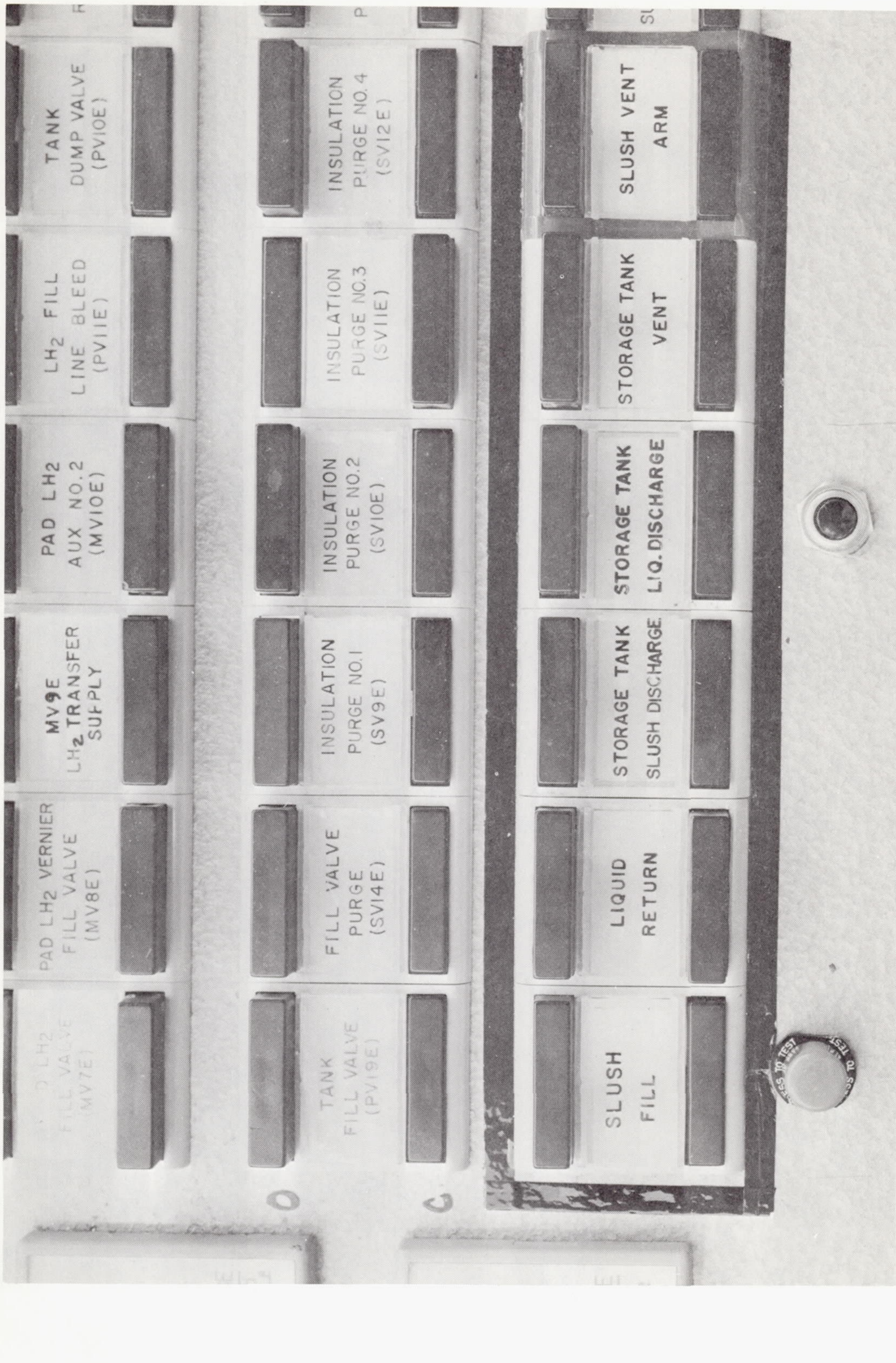


Fig. 4-3 Slush Hydrogen Test Control Console

Section 5
CALIBRATION AND CHECKOUT PROCEDURES

All instrumentation and data-acquisition system components that were used to obtain the contract test data were previously calibrated by the Lockheed Measurement Standards Laboratory (MSL) and/or the Instrument Calibration Repair Laboratory (ICRL). In addition, in-place calibrations and checkouts of complete systems as installed were performed to obtain better correlation of temperature, pressure, liquid-level, and weight measurements. Details of these calibration and checkout procedures are presented in this section.

5.1 CALIBRATION OF THE WEIGHING SYSTEM

A number of preliminary calibration tests were performed to determine the sensitivity, linearity, repeatability, and basic accuracy of the propellant weighing system. Initially, calibrations were performed on the load-cell alone, by both MSL and ICRL. Later, complete system calibrations at ambient and liquid nitrogen temperatures were performed in the vacuum chamber. The final system calibrations were obtained at liquid hydrogen temperatures in the vacuum chamber.

5.1.1 Preliminary Calibrations

Results of all of the preliminary weighing system calibrations are presented in Fig. 5-1. The data points shown in the figure represent the actual deviations in magnitude between the applied weights and the calculated weights where the calculated weights were obtained from a least-square straight line curve fit through the data obtained from any particular calibration test. The calibration description, date, calculated output slope, and zero offset are noted for each calibration test. Class B sealer weights, with accuracy traceable to the National Bureau of Standards, were used in performing these calibrations.

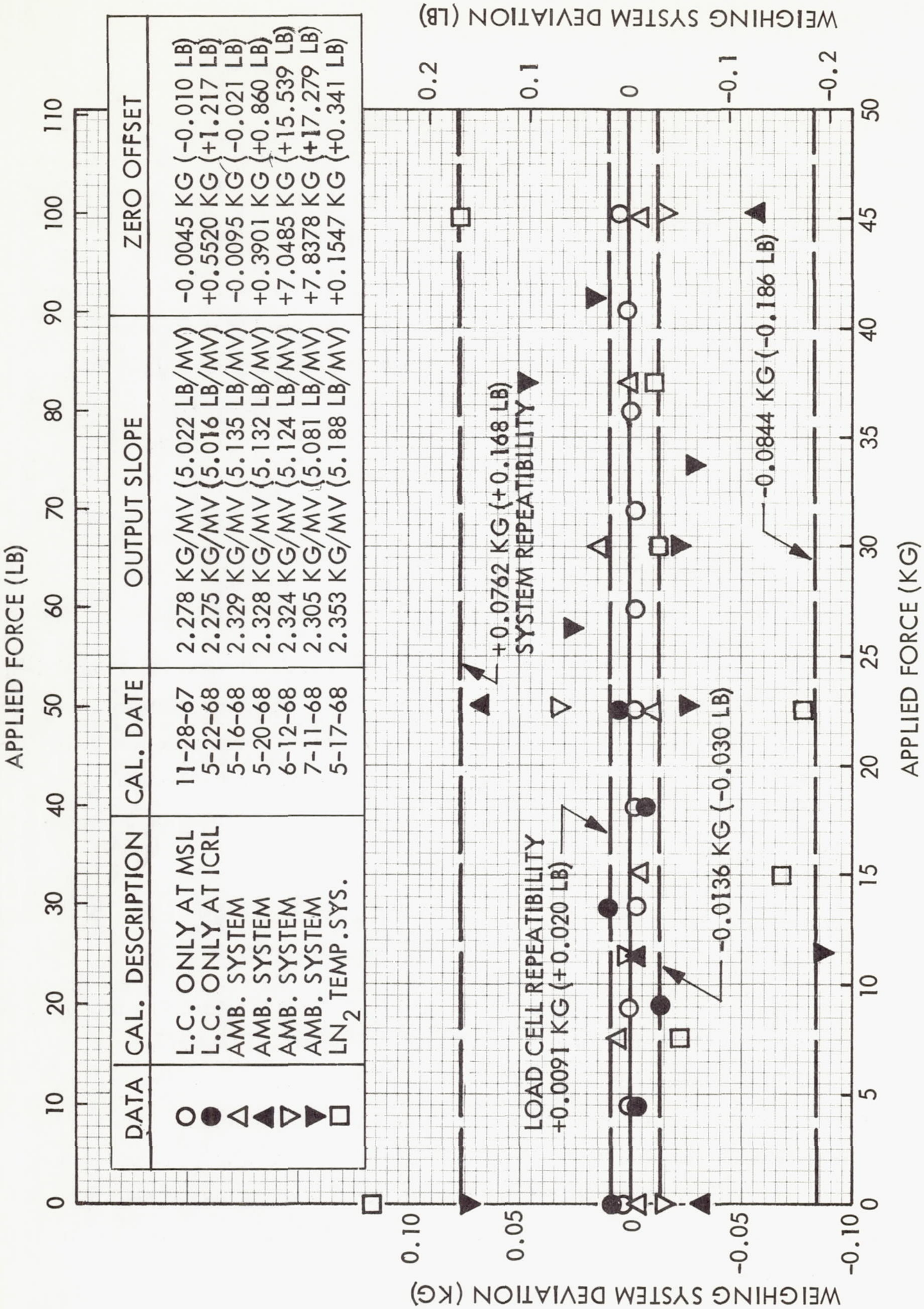


Fig. 5-1 Weighing System Calibration at Ambient and LN_2 Temperatures

It can be seen by inspection of the data presented in Fig. 5-1, that the slope of the curves obtained from laboratory calibrations of the loadcell alone is quite repeatable, and that the weight deviations are within ±0.0136 kg (±0.03 lb) throughout the range of applied force. It can also be seen that the slope of the curves obtained from the total system calibrations is somewhat greater and less repeatable, and that the corresponding range of weight deviations increases to approximately ±0.0844 kg (±0.186 lb). The increased slope of the curves for the total system is believed to be due to mechanical restraint of the system from bending of the plumbing and the flexural pivots. The difference in a calculated full-scale weight measurement of the system is approximately 0.91 kg (2 lb) due to this difference of slope, but does not represent a weighing error per se, so long as a total system calibration with known weights is used.

The ambient system calibrations performed on 16 May, 20 May, and 12 June (Fig. 5-1) all resulted in curve slopes of approximately 2.327 kg/mv (5.130 lb/mv). These calibrations showed that the basic repeatability of the system was satisfactory. During the interval of time between these calibrations, the system was modified to permit more accurate measurement of the loadcell excitation voltage so that all later data could be corrected for any drift that occurred in this voltage during a test. Subsequently, it was determined that a large weighing error resulted from internal pressure relief of the loadcell as the chamber was evacuated. This occurred because the loadcell was not vented to equalize internal and external pressures. When this was determined, the loadcell was removed from the system, venting holes were drilled in the housing, the loadcell was reinstalled, and the ambient system calibration of 11 July was performed. A 2.305 kg (5.081 lb/mv) curve slope resulted from this calibration. The change in the slope is thought to be the result of slight geometry variations that occurred between the original installation and the final installation. Subsequent loadcell data, taken during pumpdown of the vacuum chamber showed that the venting of the loadcell housing completely eliminated weighing errors that previously resulted from pressure effects.

The results of the calibration at liquid nitrogen temperature on 17 May are shown in Fig. 5-1, but these are considered to be inconclusive because this calibration was performed prior to insulation of the tank and plumbing (to avoid moisture damage to the

insulation), and the variable weight of frost that formed on the outside surfaces could not be accurately determined. It is interesting to note that a frost thickness of approximately 0.025 cm (0.01-in.), applied at the full-scale load, would account for the change of slope that occurred.

The minimum discrete weight increment to which the weighing system is sensitive was determined to be approximately 5 grams (0.011 lb) during the preliminary system calibration tests.

5.1.2 Final Calibration

During checkout of the test apparatus with liquid hydrogen, calculations were performed to determine whether the slope of the loadcell output curve and the zero-load offset value determined during preliminary testing were valid with the system chilled to liquid hydrogen temperatures. The weight of the liquid based on density and volume with the tank filled to optical sensor waterlines, and the zero-weight reading during draining were used in the calculations. The test data used was carefully evaluated to correlate temperature and pressure measurements to ensure that the liquid was in fact saturated at known conditions. It was found from these calculations that both the slope and the zero offset values did change between ambient and liquid hydrogen temperatures.

In order to obtain a satisfactory calibration curve for the weighing system at liquid hydrogen temperatures, a least-squares curve fit was then performed using measured versus calculated weight values from the test data. Data points were obtained with the tank empty and filled to the OS-2 sensor (78.50-percent waterline) and the OS-3 sensor (90.47-percent waterline). Again, only those data points were used where temperature and pressure measurements indicated saturation conditions existed. Three independent zero-load data points were obtained during draining operations. Data points at the optical sensor waterlines were obtained during both filling and draining operations. A total of 6 independent points were obtained at the 78.5-percent waterline, and one additional point was obtained at the 90.47-percent waterline.

Results of the final weighing system calibration are presented in Fig. 5-2. The data points shown in the figure represent the actual deviation in measured and calculated weights based on the least-squares curve fit. The loadcell output curve slope and zero-offset values are noted.

It can be seen by inspection of the data presented in Fig. 5-2 that the weight deviations considering all system errors (weight, liquid-level, and density) are within approximately ±0.454 kg (±1.0 lb) throughout the range. This magnitude of deviation is approximately equivalent to ±10 percent in slush quality, where weight and volume at the 78.5-percent waterline are used to determine the nominal slush quality.

5.2 CALIBRATION OF LIQUID AND SLUSH LEVEL SENSORS

During the contract test program, liquid and slush levels in the test tank and dewars were monitored in order to control the hydrogen quantities and the flow rates within desired limitations. In the test tank, the outputs of optical point level sensors were recorded and later used to calculate liquid and slush densities. These optical sensors were also used as a primary reference in order to adjust the output meter readings of the continuous capacitance sensors used in the test tank as control devices. The number and exact locations of the test tank sensors are discussed in subsection 3.7.

A combination of thermocouples, carbon resistor point sensors, and a single optical point sensor were provided in the storage dewar and used to determine the approximate liquid and slush levels in the dewar during the tests. These sensors and their location in the dewar are discussed in subsection 2.1.3.6.

Liquid and slush levels in the manufacturing dewar were observed visually through the dewar windows during slush manufacture and transfer operations.

5.2.1 Optical Sensors

Repeatability and time response of this type of sensor have been investigated by the National Bureau of Standards. Results were published in 1963 in "The Performance of

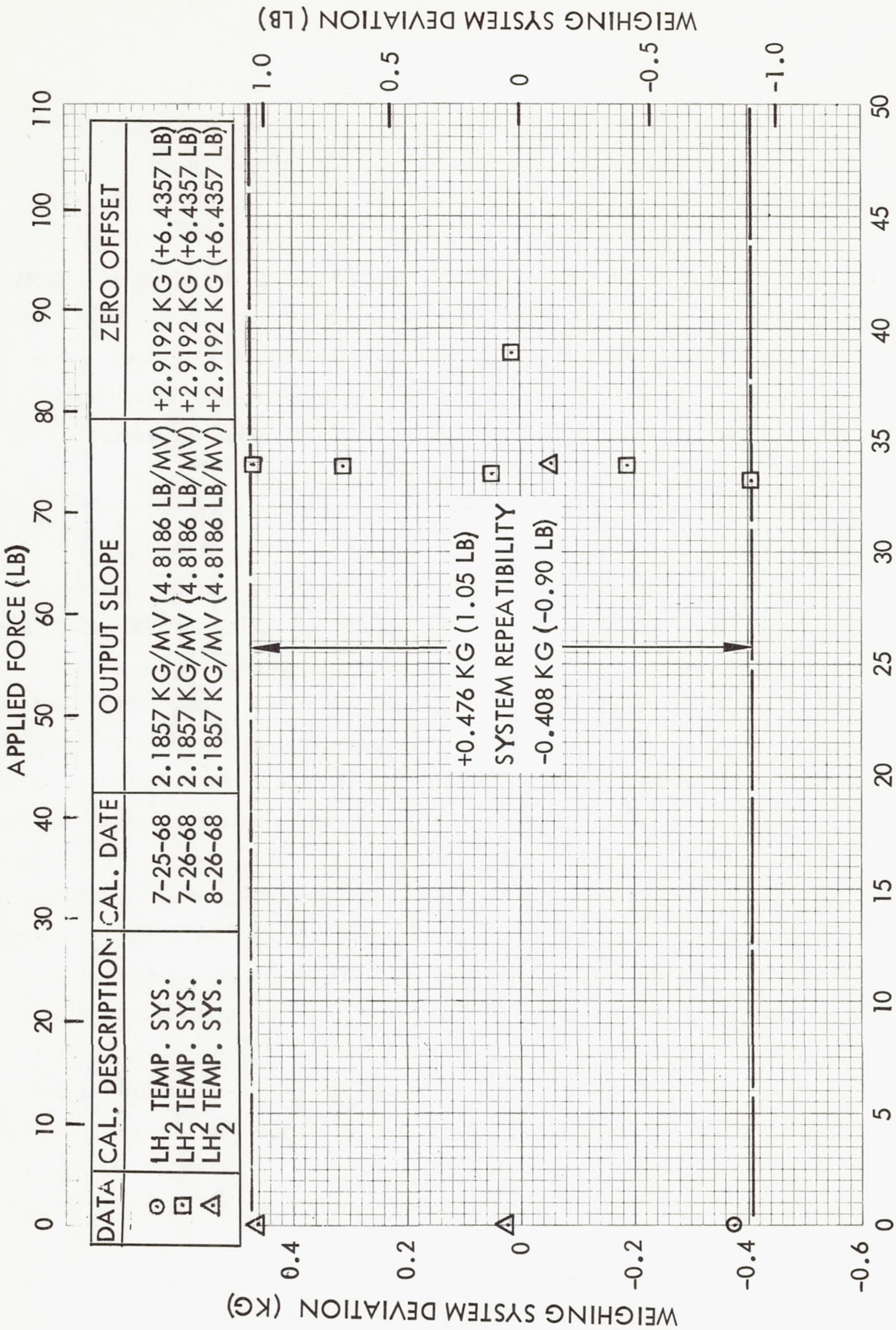


Fig. 5-2 Weighing System Calibration at LH_2 Temperature

Point Level Sensors in Liquid Hydrogen," by Burgeson, Pestalozzi and Richards (R-292, Cryogenic Data Center, NBS, Boulder, Colorado). The repeatability error band was shown to be 0.686 mm (27 milli-in.) and the time response error band to be 417 millisec. Lockheed tested three optical liquid level sensors in April 1966 at the Primary Standards Laboratory with water and with liquid nitrogen, and found the repeatability error band to be 0.508 mm (20 milli-in.). It was also determined during these tests that the power supply sensitivity of the sensors tested was 0.152 mm/volt (6 mils/volt) excitation.

Based on these results, a conservative level error of ± 2.54 mm (± 0.1 in.) was assumed in determining the probable volume and propellant density errors. At the 78.5-percent waterline where the OS-2 sensor is located this level uncertainty corresponds to approximately $\pm 1858\ \text{cm}^3$ ($\pm 0.0656\ \text{ft}^3$), or approximately ± 0.143 kg (± 0.315 lb) of triple point liquid hydrogen. The comparable volume and weight uncertainties are $\pm 1371\ \text{cm}^3$ ($\pm 0.0484\ \text{ft}^3$) and ± 0.106 kg (± 0.233 lb), respectively, at the 90.47-percent waterline where the OS-3 sensor is located.

Prior to conducting the slush hydrogen manufacturing test described in subsection 6.1, a Bendix Model GT 103 optical sensor was temporarily mounted inside the slush manufacturing dewar so that it could be calibrated to sense a liquid-slush interface. In order to mount the sensor, one of the glass viewports was removed and temporarily replaced with a blank stainless-steel O-ring-sealed flange. A standoff was welded to the inside of the flange to support the sensor, and a standard O-ring-sealed bulkhead electrical feedthrough connector was installed in the flange to provide electrical power and output circuits. The sensor was positioned inside the dewar so that it was slightly below the liquid-vapor interface when slush was being manufactured. The electrical power supply was then adjusted so that the sensor output circuit was completed (sensor light on) when the sensor was covered with clear liquid, and interrupted (sensor light off) when the sensor was covered with either slush or ullage vapor. The sensor was operated satisfactorily several times during this calibration, but subsequently failed to operate when installed in the storage dewar. The cause of the failure has not been determined to date.

5.2.2 Continuous Capacitance Sensors

During contract testing, the outputs from the continuous capacitance level sensors located in the test tank were displayed on a zero-centered microammeter at the control console and used only as a visual control aid to the test conductor. These outputs were not recorded or used in subsequent data reductions; however, this would be desirable in future tests to expand the knowledge of liquid-level time histories. Data obtained during the calibration of these sensors in liquid hydrogen prior to installation in the test tank indicated a maximum liquid level uncertainty of approximately ±0.33 cm (±0.13 in.).

The upper continous capacitance sensor located at the 90.69-percent waterline in the test tank was inoperative during the slush flow tests. It was subsequently determined that the electrical passthrough connector that accommodated output and excitation circuits for this sensor had loosened, possibly due to thermal action during numerous chilldown and warmup cycles.

5.3 SPECIAL TEMPERATURE CALIBRATION EQUIPMENT

All low-temperature calibrations performed by the Lockheed Measurement Standards Laboratory during the past several years have been accomplished using vacuum-insulated liquid helium cryostats. Early in 1968, an improved cryostat was developed jointly by the MSL and Cryogenic Stage Programs and placed into operation. This cryostat has subsequently been used to perform all temperature sensor calibrations for this program. Figure 5-3 is a sketch showing the cryostat in cross-section.

The cryostat is vacuum-jacketed as well as multilayer-insulated, and makes use of a liquid nitrogen shield to effectively reduce heat transfer into the cryostat. All temperature sensors to be calibrated in a particular run are mounted together with one or more standard thermometers, calibrated by and traceable to the NBS, into a solid aluminum block approximately 25.4 cm (10 in.) in diameter. The block is supported by four copper rods that rest on the bottom of the inner vessel. During operation of

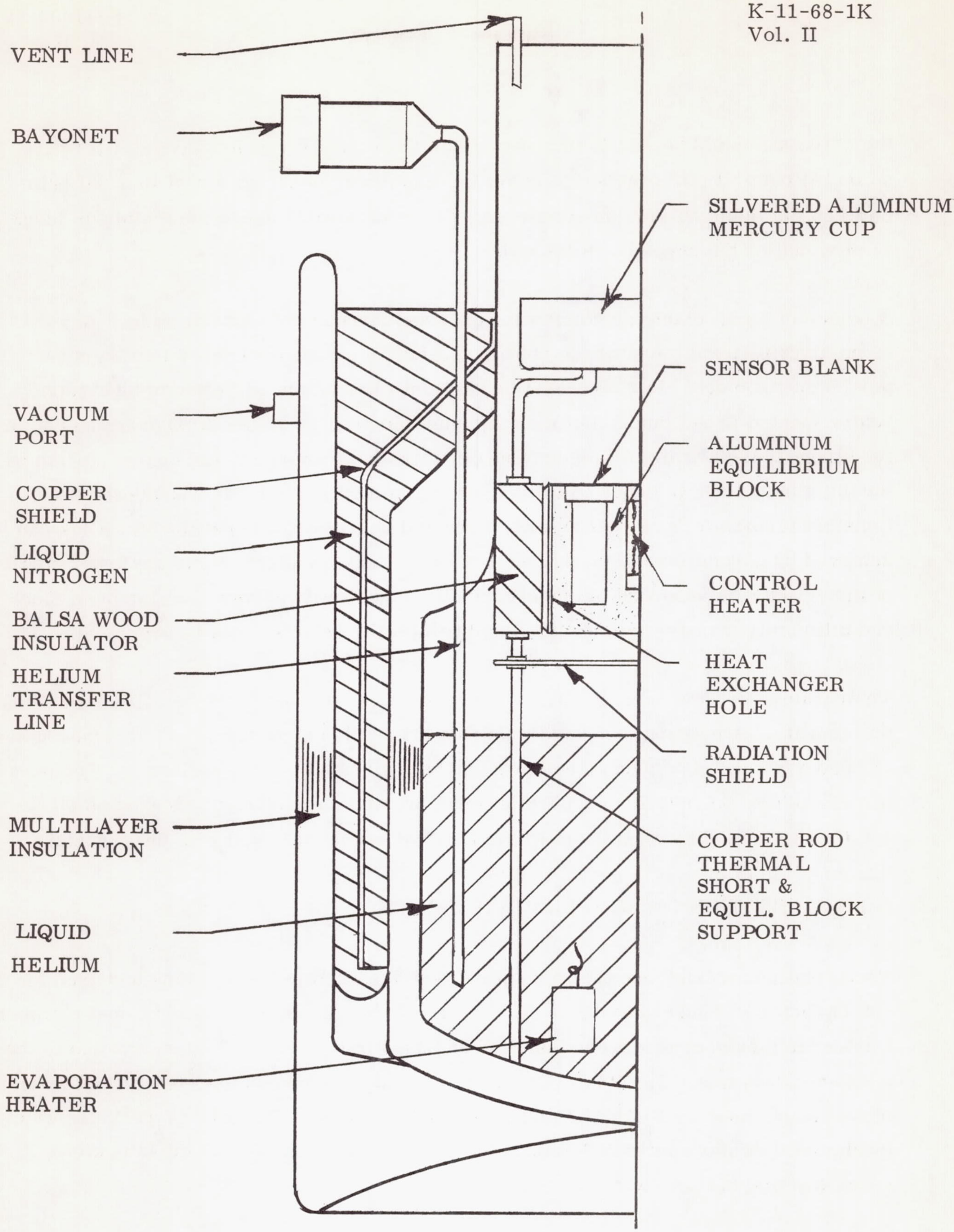


Fig. 5-3 Cross-Section Schematic of Low Temperature Sensor Calibration Cryostat

the cryostat, liquid helium is introduced into the vessel through a bayonet fill fitting so that it partially fills the space below the aluminum block. A direct thermal path between the liquid helium and a mercury-filled cup located above the aluminum block is provided by the copper support rods.

A series of small diameter holes were provided through the aluminum block in a circular pattern surrounding the sensor receptacle cavities recessed into the upper portion of the block. During operation, helium vapors formed by use of an electric heater located in the liquid cool the aluminum block as they rise through the holes into the ullage space above. An electric heater was also provided in the center portion of the aluminum block in order to raise the temperature of the block when desired. Constant temperature as well as increasing and decreasing temperature profiles can be achieved by careful control of the two heaters. Heat transferred into the upper portion of the cryostat is absorbed by a mercury-filled cup located above the aluminum block and ultimately transferred into the liquid helium through the copper support rods.

Temperature sensors of 2.54 cm (1.0 in.) or less in diameter can be calibrated using this facility. A maximum of 8 platinum resistance thermometers or 50 thermocouples or bead-type resistance thermometers can be calibrated in any single run. Temperatures stable to $\pm 0.001°K$ ($\pm 0.0018°R$) for 1 hr, and measurement accuracies of $\pm 0.1°K$ ($\pm 0.18°R$) with traceability to the NBS can be achieved with the cryostat.

5.4 CALIBRATION OF TEMPERATURE SENSORS

Three platinum resistance thermometers were installed in the test tank and used to obtain recorded temperature data during the contract tests. Single additional platinum resistance thermometers were installed and used in both the storage dewar and in the test tank drain line. The RTB-1 and RTB-2 sensors (Winsco type 2448) were located in the liquid/slush region of the tank. The RTB-3 sensor (Rosemont type 118L) was located at the intersection of the tank pressurization/vent line with the tank ullage space (Section 3.7 for exact locations).

Temperature calibration certificates are on file for the following laboratory calibrations:

Thermometer	Calibration Date	Temperature Range	Cal Performed By
RTB-1 and RTB-2	Nov 1962	21.1–273.2°K (38–492°R)	Winsco
	March 1968	4.4–77.0°K (8–138.6°R)	Lockheed MSL
	Sept 1968	4.4–77.0°K (8–138.6°R)	Lockheed MSL
RTB-3	Oct 1966	4.4–273.2°K (8–492°R)	Rosemont

It was determined during the September 1968 calibration that data obtained below approximately 22.2°K (40°R) during the March 1968 calibration was invalid due to malfunction of the primary standard platinum resistance thermometer used as the reference for that calibration. The September 1968 calibration was performed using the original standard platinum thermometer and a new standard platinum thermometer as well as a germanium thermometer.

In addition, RTB-1 and RTB-2 data points were evaluated over a temperature range of approximately 17.5–20.0°K (31.5–36°R) during tests with saturated liquid hydrogen in the test tank. These tests were performed by initially chilling and filling the tank with liquid hydrogen, and then allowing it to reach a saturated equilibrium condition by venting it to the atmosphere. Subsequently, the tank ullage pressure was slowly reduced by vacuum pumping, and saturation temperatures were determined by observing and correlating pressure transducer readings from three separate pressure sensors.

Figure 5-4 shows the comparison of the September 1968 laboratory calibration with the liquid test data points. The calibration curve was derived by use of the Corruccini interpolation equation and the temperature-resistance relationships of the new standard

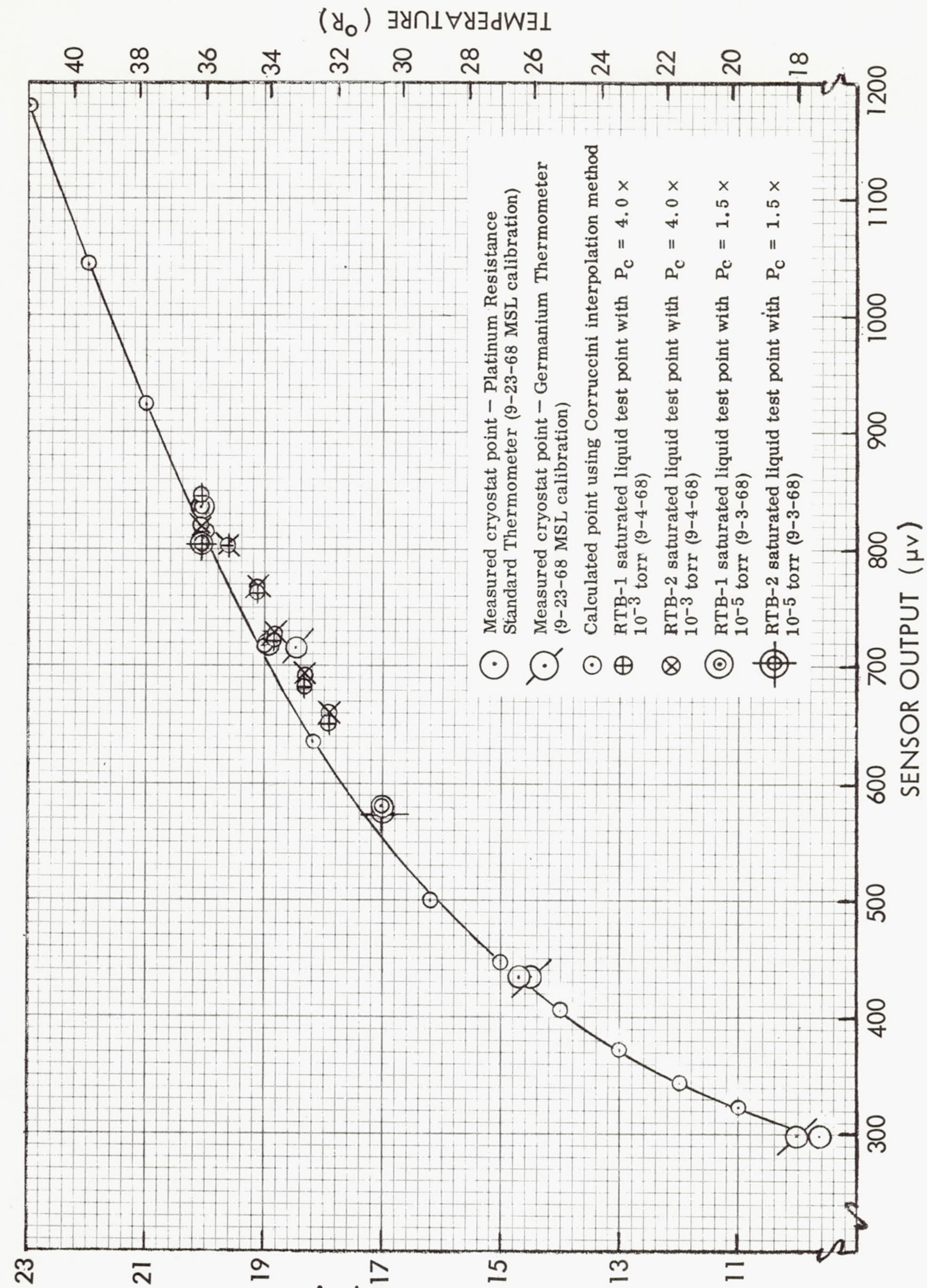


Fig. 5-4 Temperature Sensor Calibration and Test Data Correlation

platinum thermometer. The curve was fitted in two separate segments between measured end points at 10.025°K (18.045°R) and 18.43°K (33.174°R), and between 18.43°K (33.174°R) and 77.00°K (138.600°R). The liquid test data points shown were corrected for both excitation voltage drift and measured thermoelectric effects across the Deutsch electrical feedthrough connector pins that accommodate the RTB circuits. The latter corrections were obtained by observing consecutive RTB readings with the excitation voltage applied in both nominal and reversed polarities, and by then using half of the difference in the two readings as the magnitude of the correction. The corrections thus obtained ranged from 5 to 40 microvolts, and did not vary appreciably between readings at 17.5 and 20.0°K (31.5 and 36°R). It is not known whether these corrections are valid for readings taken near the triple point; however, an uncertainty of approximately ±40 microvolts was assumed in subsequent temperature correlations with weight/volume data obtained with slush in the tank. It can be seen by inspection of Fig. 5-4 that a ±40 microvolt uncertainty is equivalent to approximately ±1.1°K (±2°R) at the triple point of hydrogen.

Based on these results, it is clear that platinum resistance thermometers have limited application for slush hydrogen testing. It was concluded that germanium thermometers would provide significantly better temperature measurement accuracies in this range.

5.5 CALIBRATION OF PRESSURE SENSORS

Three Statham unbonded strain gage type 0−34.5 N/cm^2 gage (0−50 psia) pressure transducers were installed and used to monitor and record test tank pressure during the contract tests. Similar sensors were used to obtain pressure data in the manufacturing and storage dewars, and in the test tank drain line. Two of the test tank pressure sensors were mounted on a short standoff to the pressurization-vent line approximately 25.4 cm (10 in.) from the interface with the tank ullage space. The third was located outside the vacuum chamber passthrough, approximately 9.1 m (30 ft) from the test tank.

These sensors were all precalibrated by the ICRL at 22.2°C (72°F) to an accuracy of ±0.3 percent of full scale, or ±0.10 N/cm^2 (±0.15 psia) traceable to the NBS. Calibration curves of output millivolts versus applied pressure were constructed from 5 points of increasing and 5 points of decreasing applied pressure. These curves were subsequently used to reduce all data obtained during contract testing.

Correlations of test data show agreement among the three test tank sensors within approximately ±0.17 N/cm^2 (±0.25 psia) throughout the testing. These sensors also agreed with barometric pressure readings within ±0.17 N/cm^2 (±0.25 psia), where the tank was filled with saturated liquid hydrogen and vented to the atmosphere.

Section 6
PRELIMINARY TEST PROCEDURES AND RESULTS

A number of preliminary system tests were conducted to qualify and/or calibrate particular hardware components, and to obtain additional engineering data needed to complete the contract test program plan prior to performing the slush flow tests. These tests included (1) manufacture and transfer of slush nitrogen and slush hydrogen, (2) determination of the time required to pumpdown the vacuum chamber pressure, (3) determination of the test tank ground-hold heating rate, (4) checkout of test apparatus instrumentation and control components with liquid cryogens, and (5) a storage dewar boiloff test. Results of these preliminary tests are presented in the following paragraphs.

6.1 MANUFACTURE AND TRANSFER OF SLUSH NITROGEN AND SLUSH HYDROGEN

Preliminary slush manufacturing tests were conducted subsequent to final installation of the slush manufacturing and transfer system hardware to qualify the facility. These tests consisted of the manufacture and transfer of two batches of slush nitrogen and a single batch of slush hydrogen. The pumping time to achieve triple-point conditions, and to then produce a batch of slush were compared with those previously predicted by analysis.

It was found from these tests, that the manufacturing dewar, the manufacturing dewar vent gas heat exchanger, and the vacuum-pumping system performed essentially as planned. However, the time required to vacuum-pump the cryogen from its initial atmospheric-saturated condition to the triple-point condition was slightly longer than predicted. This was due to an inherent heat transfer limitation of the vent gas heat exchanger as designed. During the initial part of the cycle when the mass flow rate of the gas was highest, it was found to be necessary to throttle the flow to the vacuum

pumps by partially closing the shutoff valve to maintain the gas temperature at the inlet above the minimum specified for the pumps.

Subsequent to the qualification pumping tests, a temperature sensor was installed in the vacuum-pumping line near the inlet to the pumps. During later manufacture of slush for the contract tests, this sensor permitted control of the system to minimize the pumping time without decreasing the vent gas temperature below the minimum specified pump inlet temperature of 200° K (360° R).

The slush nitrogen manufacturing tests were conducted using only one of the two vacuum pumps described in Section 2.1.3.2, and using a hand-operated shutoff valve in the vacuum-pumping line. The other vacuum pump (a replacement for one previously damaged) was installed and checked out during the slush hydrogen manufacturing test. Also, the Heraeus-Englehard remotely-operated shutoff valve described in Section 2.1.3.2 was installed and checked out during that same test.

During these preliminary slush manufacturing tests, it was determined that the mechanical agitator and its rotary drive feedthrough, the viewports, the dewar insulation system, the fill and drain plumbing, and the pressurization and vent plumbing all performed as planned. Also, it was determined that no leakage of air into the system occurred during any of these tests.

6.2 DETERMINATION OF THE TIME REQUIRED TO PUMPDOWN THE VACUUM CHAMBER PRESSURE

Control of the environmental heat rate into the test tank during all contract tests was achieved by initially evacuating the vacuum chamber to remove air molecules and by then backfilling to a desired partial pressure with GHe. It was therefore necessary to determine reasonably accurate pressure-time relationships for these pumpdown operations prior to initiating slush flow tests in order to predict the resulting total quantity of heat that was ultimately transferred into the test tank as a function of chamber pressure, and the quantity of slush that was melted from that heat. In addition, it was necessary to determine in advance whether the desired partial pressure

of GHe could be adequately controlled in the vacuum chamber during the slush flow tests.

Pressure-time data was obtained from two different pumpdown tests of the vacuum chamber after the test apparatus was installed, insulated, and checked out. These data are presented in Fig. 6-1. In addition, it was determined during the groundhold heat-rate boiloff tests (see Section 6.3) that a desired constant chamber pressure could be maintained with liquid hydrogen in the test tank by locking up the vacuum chamber without additional purging and/or vacuum-pumping.

6.3 DETERMINATION OF THE TEST TANK GROUNDHOLD HEATING RATE

Thermal performance of the test tank insulation system was predicted by analysis and subsequently confirmed by boiloff testing for the initially planned groundhold test condition. Boiloff tests were conducted using atmospheric-saturated liquid hydrogen, and the results were then adjusted analytically to account for the slight increase in temperature differential that would exist with slush in the tank. Figure 6-2 shows the predicted and measured thermal performance as a function of vacuum chamber pressure. Actual test points are shown in the figure at chamber pressures of 16 torr and 38 torr, and at the planned groundhold slush test pressure of 50 torr. The planned test condition was based on a desired heat flux of approximately 630.6 w/m^2 (200 Btu/hr ft^2), which is equivalent to a total heat rate of approximately 2452 w (8370 Btu/hr) as shown.

During performance of the first slush flow test, excessive heat transfer into the slush line outside of the vacuum chamber prevented successful transfer of slush to the test tank. Accordingly, the second and third slush transfer tests were performed with the vacuum chamber at reduced pressures ranging from 1.5×10^{-5} torr to 1.0×10^{-2} torr to minimize slush melting.

In performing all tests, the vacuum chamber was completely evacuated to 10^{-5} torr to remove all air molecules and then backfilled with helium to achieve the desired

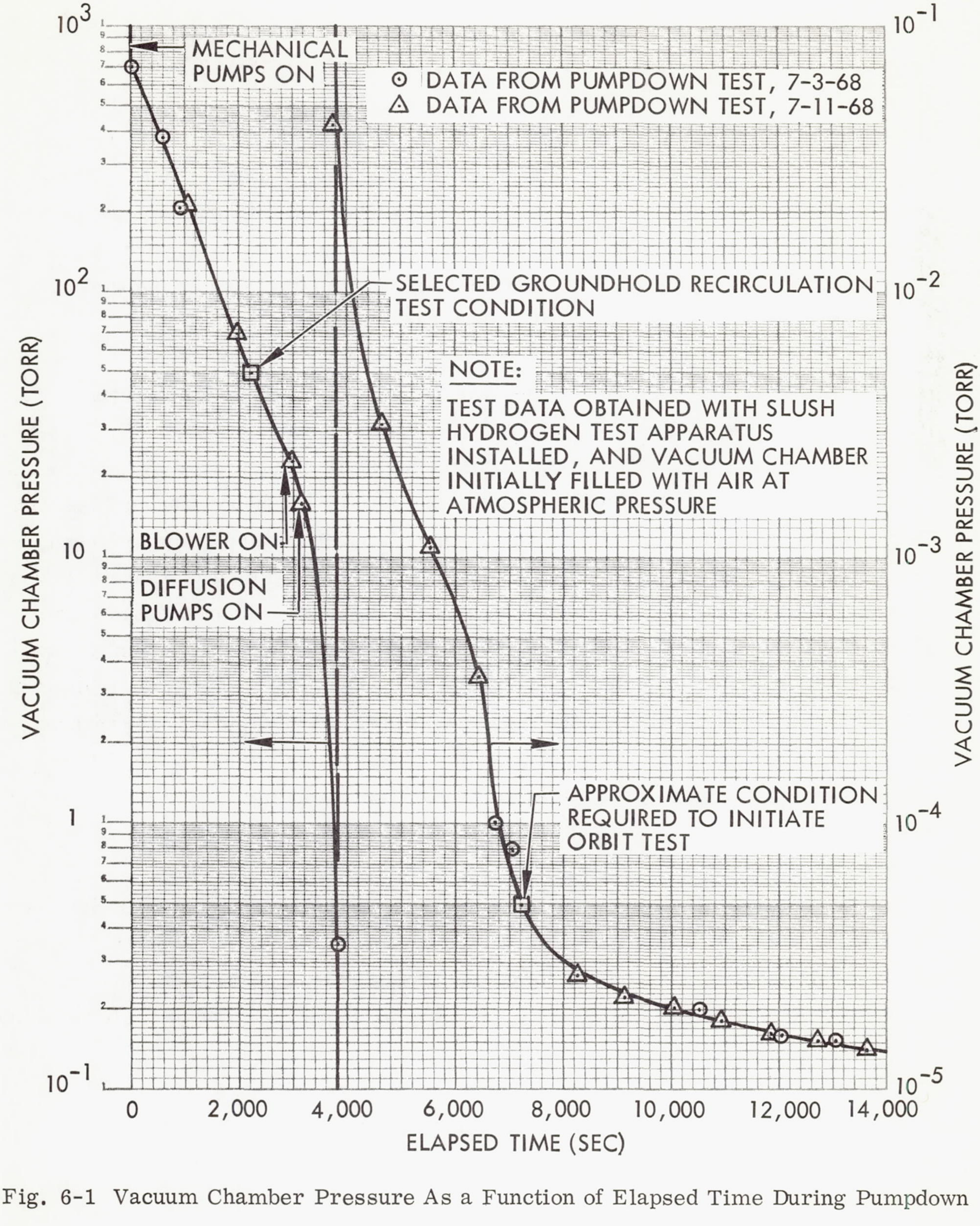


Fig. 6-1 Vacuum Chamber Pressure As a Function of Elapsed Time During Pumpdown

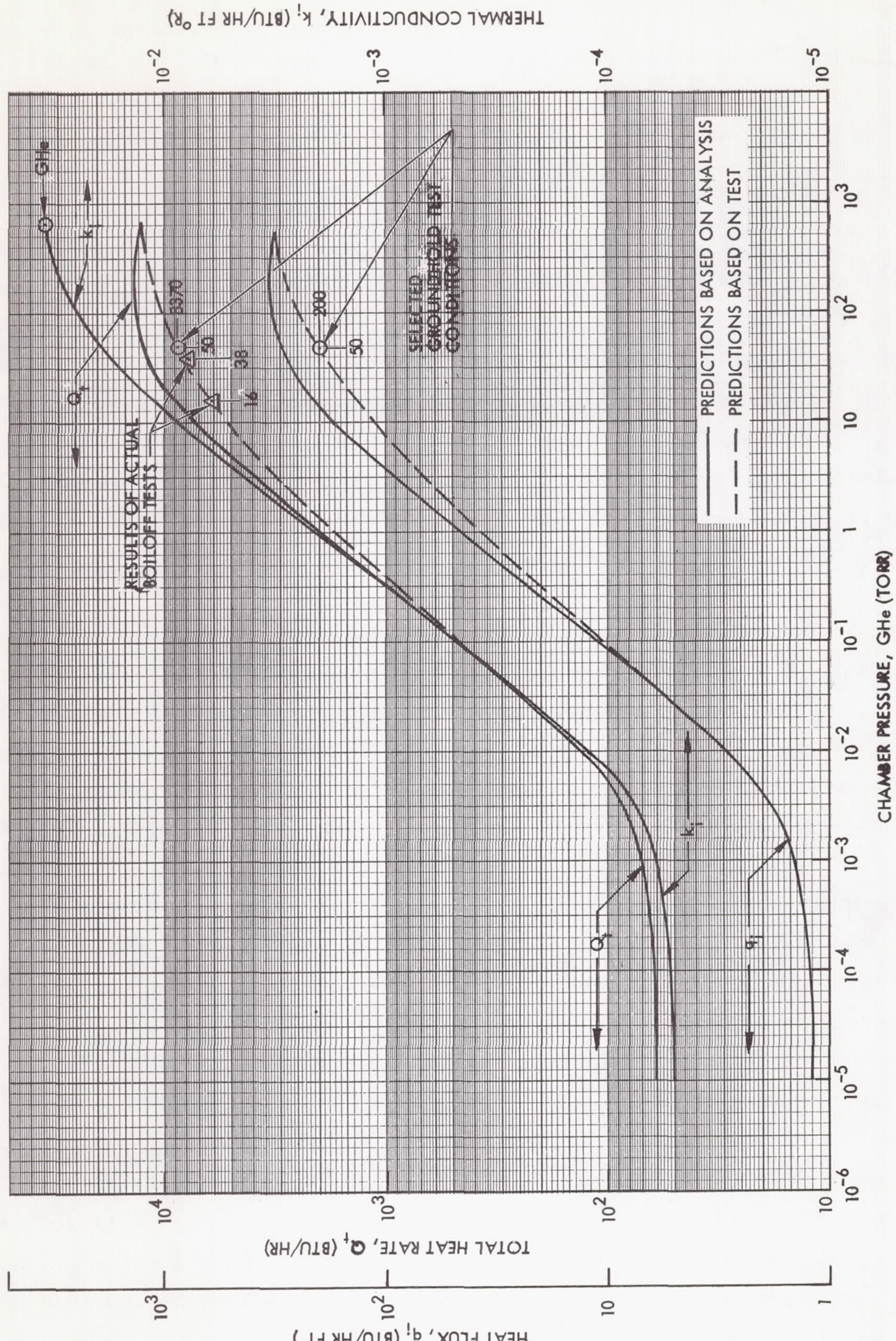


Fig. 6-2 Thermal Performance of Insulation System

test conditions. It was found during the preliminary boiloff tests that the chamber pressure could be maintained at a constant value without additional pumping or helium flow. A purge bag around the insulation system was not required or provided since only helium was present in the chamber using this technique.

6.4 CHECKOUT OF TEST APPARATUS INSTRUMENTATION AND CONTROL COMPONENTS WITH LIQUID CRYOGENS

During the groundhold heat-rate boiloff tests described in Section 6.3, all instrumentation and control components in the test apparatus were also checked out with liquid hydrogen. In addition, the capacitance-level sensors had already been calibrated in liquid hydrogen, and the Deutsch electrical feedthrough connectors had been subjected to one or more thermal-shock and helium-leak tests each. Liquid nitrogen and liquid hydrogen were used for the connector qualification tests.

All valves and plumbing components performed as planned. There was no evidence at that time of any leakage through Conoseals, electrical feedthroughs, or from any other source. Liquid hydrogen was transferred through each line including the liquid fill and drain line, the slush fill line, and the liquid-return (recirculation) line with excellent results. Also, the pressurization, vent, helium purge, and hydrogen heat exchanger components were exercised with no apparent malfunctions or problems.

During the initial chilldown and fill of the test tank, the two capacitance level-sensors were adjusted to provide the proper zero and full-scale readings on the control console. The upper one of these became inoperative during the chilldown and could not be used (see discussion in Section 5.2.2).

All pressure and temperature sensors, the drainline flowmeter, and the two Globe slush mixers were exercised during these preliminary liquid hydrogen tests with satisfactory results. It was determined during the tests that some excitation voltage power supply drift did occur. Consequently, all power supplies were rechecked, and excitation voltage printout channels were installed for all the affected instrumentation sensors. This permitted analytic correction of the test data where that was found to be necessary.

6.5 STORAGE DEWAR BOILOFF TEST

Subsequent to installation and leak checkout of the 3.0 m^3 (804-gal) storage dewar, a liquid hydrogen boiloff test was performed to determine the actual thermal performance of the dewar. The dewar was chilled, filled with liquid hydrogen, and then allowed to approach apparent equilibrium over a period of approximately 8 hr. The steadystate boiloff rate during the last 2 hr of the test indicated a total heat transfer into the dewar of approximately 17.6 W (60 Btu/hr), which was within 1 percent of the analytically predicted value calculated at the beginning of the dewar design.

6.6 FLIGHT SIMULATOR LEAKAGE TESTS

Liquid hydrogen was transferred into the storage dewar for the boiloff test from the 49.2 m^3 (13,000-gal) supply dewar, through the test tank plumbing system. The vacuum chamber had been pumped to a pressure of approximately 1.0×10^{-5} torr prior to initiating the liquid hydrogen transfer. A leak occurred inside the vacuum chamber late in the transfer operation that resulted in rapid pressurization of the chamber to near atmospheric pressure with considerable back-streaming of oil from the diffusion pumps. Subsequently, the test tank was inerted and the vacuum chamber was opened to permit removal of the oil and inspection of the apparatus to determine, if possible, where the leak had occurred so that it could be repaired. Repeated attempts to locate the leak source using helium pressurization in the test tank in conjunction with leak checking of all line and tank fittings and joints using a mass spectrometer were conclusive to the point of identifying that the chamber leak was a "cold leak," i.e., it occurred only when the system was filled with liquid hydrogen. Ultimately, several suspected line fittings and seals were replaced and/or tightened and the chamber was closed and re-evacuated.

During all of the subsequent slush flow tests, it was found that the vacuum chamber pressure could not be maintained below approximately 1.0×10^{-2} torr without some vacuum pumping. However, the leakage rate was never sufficiently large to permit

determination of the source so that it could be repaired. During the third slush-flow test, the additional heat load on the test tank due to higher-than-desired chamber pressures caused by the leakage required that the chamber be repumped between manufacture of each slush batch. The chamber was maintained at pressures between 1.0×10^{-3} and 8.0×10^{-3} torr during the third flow test using this technique. Since slush was successfully transferred into the test tank during the test, it is considered that the vacuum chamber leak had little impact on the slush hydrogen test results.

Section 7
FINAL TEST PROCEDURES AND RESULTS

Two groundhold recirculation tests and one ascent/orbit test were planned initially to be conducted during the contract program. Three recirculation flow tests were actually performed. The first was with the test tank subjected to the planned groundhold heat-load environment, while the second and third were performed with the tank subjected to reduced heat environments typical of ascent and orbit conditions. During the second and third tests, propellant storability and draining sequences at reduced heat environments were also performed.

The total durations of the first two flow tests were approximately 48 hr each. Test operations were conducted continuously, using two 12-hr shifts of test personnel each day. The duration of the third test was approximately 12 hr.

Slush hydrogen was manufactured in 0.132-m^3 (35-gal) batches using the manufacturing dewar for all three tests. The average quality of the batches was approximately 35 percent. During manufacturing operations for the first two tests, each slush batch was pressure-transferred after manufacture into the storage dewar and accumulated. In each of these tests, flow to the 105.4-cm (41.5-in.) diam. test tank was initiated when the storage dewar had been filled to approximately 95 percent of its capacity. During the third test, each slush batch was pressure transferred after manufacture directly into the test tank.

Severe thermal oscillations occurred at transfer line bayonet fittings and values during all three flow tests. These oscillations resulted in melting of significant quantities of the solid being transferred; nevertheless the major objectives of the program were accomplished. Specific objectives that were achieved include the following:

(1) Highly successful manufacture of a total of 145 batches of slush hydrogen, equivalent to more than 18.9 m^3 (5000 gal), by test technicians with no previous specialized training

(2) Successful loading of subcooled liquid and up to 21-percent slush hydrogen into the test tank

(3) Demonstration that the recirculation technique of loading and maintaining slush in a tank is basically valid

(4) Demonstration of subcooled liquid and slush storability without venting

(5) Demonstration of subcooled liquid draining characteristics

(6) Demonstration of the suitability and performance of state-of-the-art instrumentation and test hardware components for subcooled liquid and slush hydrogen service.

Details regarding each of the three tests are presented in this section.

7.1 FIRST SLUSH FLOW TEST

The first slush flow test was conducted with the facility as shown in Figs. 2-3 and 2-4. The planned test operations included:

(1) Manufacture, transfer, and storage of approximately 2.88 m^3 (760 gal) of 50-percent slush hydrogen

(2) Filling of the pre-chilled test tank with slush to the 78.5-percent waterline

(3) Recirculation at a constant mass flow rate to maintain triple-point liquid in the tank for approximately 5 min

(4) Upgrading to achieve an average slush quality of approximately 25 percent in the tank for approximately 5 min

(5) Upgrading to achieve an average slush quality of approximately 50 percent in the tank for approximately 5 min

(6) Termination of slush flow and simulation of an ascent pressure and heat load environment

(7) Simulation of an orbit pressure and heat load environment

(8) Performance of slush storability tests

(9) Simulation of an engine firing liquid withdrawal sequence

A total of 73 batches of slush were manufactured and transferred during the first flow test. The manufacturing and storage operations were accomplished essentially as planned, except that the quality of the slush stored in the 804-gal dewar during these operations could not be determined as well as had been anticipated. It was initially planned to estimate the quality of the slush accumulated in the dewar by measuring the approximate waterline locations of both the liquid-vapor and the liquid-settled-slush interfaces using the thermocouple, carbon resistor, and optical point level sensors provided in the dewar* (see Table 2-1, subsection 2.1.3.6). If the interface locations were known, sluch quality could be readily calculated, since the density of settled slush is well known as a function of aging time from previous NBS work. However, thermocouple readings taken during the accumulation of slush for the first flow test were inconclusive with regard to indicating the presence of solid, or (if solid were present), the liquid-settled-slush interface location. These readings did indicate the approximate location of the liquid-vapor interface, that the stored hydrogen was approximately at triplepoint temperature, and that the temperature profile was essentially constant from the top of the dewar to the bottom (i.e., negligible stratification). The difficulty in positively establishing the presence of solid in the dewar, or the location of the liquid-settled-slush interface, was due primarily to the fact that the temperature of fluid surrounding the reference thermocouple located near the bottom of the dewar could not be determined with sufficient accuracy. It had been planned to establish the fluid temperature using the platinum thermometer located near the reference thermocouple. During the test, the output of this thermometer was approximately 25 μv lower than that corresponding to triplepoint temperature; however, it was later determined in a post-test recalibration that the uncertainty of the platinum thermometer output near triplepoint temperature is approximately ± 40 μv due to thermoelectric and other effects (see discussion of accuracy in Subsection 5.4). Another factor that contributed to the difficulty of determining slush quality from the thermocouple readings was the tendency toward an isothermal temperature distribution in the dewar inner vessel shell due to its relatively high thermal conductance. The high

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*Thermocouples have been used successfully by NBS personnel to detect these interfaces in the receiver dewar of the slush flow loop located at the NBS Boulder facility.

conductance resulted from the combination of high thermal conductivity of the aluminum* and the 0.635-cm (0.25-in.) thickness of the shell. Temperature stratification in the hydrogen was therefore lower than what would have been expected in an equivalent steel-shell dewar with the same average heat flux.

Simultaneous to the slush manufacturing and storage operations, the vacuum chamber was evacuated and backfilled with GHe to a pressure of 50 torr to achieve the desired groundhold heat load of approximately 631 w/m^2 (200 $Btu/hr\text{-}ft^2$), or 2452 w (8370 Btu/hr) total on the test tank. The test tank and all transfer lines were then chilled with liquid hydrogen from the facility storage dewar. The test tank was subsequently drained just prior to initiation of the slush recirculation flow test.

During the recirculation flow test, visual displays at the control console of outputs of the propellant weighing system, liquid level sensors, and temperature sensors in the tank indicated that only approximately atmospheric-saturated temperature liquid was flowing into the test tank. In addition, it was found that the liquid level could not be adequately controlled at the desired water-line when the liquid recirculation valve was first opened. It was subsequently determined that the recirculation line was not completely chilled prior to the time the valve was opened. The difficulty in controlling the flow was therefore considered to be due to flashing of liquid into vapor in the warm line with choked-flow conditions resulting.**

Reduction and evaluation of the data recorded during the first flow test confirmed the observations made during the test. The average temperature of the liquid in the tank during the test was approximately 20°K (36°R), with a minimum temperature of

*The thermal conductivity of aluminum at the hydrogen triplepoint temperature of 13.8°K (24.85°R) is approximately 0.12 w/cm °K (7.0 Btu/hr ft °R) compared to approximately 0.017 w/cm °K (1.0 Btu/hr ft °R) for stainless steel at that temperature.

**This was later confirmed when proper control of liquid level was achieved during the third test where the recirculation line had been completely prechilled.

approximately 19.2°K (34.5°R). Further details of the test and data obtained from it are presented below.

7.1.1 Slush Manufacture, Transfer, and Storage

During the contract program, fundamental engineering requirements that applied to the manufacture, transfer, and storage of slush hydrogen were determined and compared to experimental results obtained by the NBS Cryogenics Division. Analyses were performed and continually up-dated to relate these requirements to the actual hardware during design, fabrication, installation, and testing. The operation of the facility and significant results of the manufacturing, transfer, and storage analyses, as they apply to all three flow tests, are discussed in this section.

7.1.1.1 Facility Operation. Briefly, the facility operation was as follows: The manufacturing dewar was purged, chilled, and filled with atmospheric-saturated liquid hydrogen by pressure-transfer from the 49.2 m^3 (13,000-gal) dewar. The dewar was then isolated from the transfer system with shutoff valves, and the ullage pressure was lowered to the triple-point pressure of approximately 0.69 N/cm^2 (1 psia) through use of the mechanical vacuum pumps. Resulting boiling and vaporization of some of the liquid hydrogen absorbed heat from the remaining bulk liquid. After the bulk temperature was reduced to the triple-point of 13.803°K (24.85°R), further pumping resulted in the formation of a layer of solid particles at the liquid-vapor interface.* Subsequently, the dewar pressure was allowed to cycle slightly above the triple-point pressure by closing a shutoff valve in the vacuum-pumping line, and was then again reduced to the triple-point pressure by opening this valve. Each layer of solid particles that formed at the triple-point pressure during each cycle settled to the bottom of the dewar as the valve was closed and the pressure increased. These cycles were repeated approximately every five sec (referred to as the "freeze-thaw" process) until the

*A photograph of the solid formation as seen through the manufacturing dewar window is shown as the frontispiece.

remaining bulk hydrogen was entirely composed of approximately 35-percent slush. The batch thus manufactured was then pressure-transferred to the prechilled storage dewar using helium pressurant precooled to liquid nitrogen temperature. The batch process was repeated until the storage dewar was filled to the desired volume level for test.*

7.1.1.2 Slush Manufacture and Storage Characteristics. A general analysis was performed early in the contract to permit analytical prediction of mass ratios and pumping times for any desired initial and final propellant conditions, manufacturing dewar heat environment, and vacuum pumping rate. Rate equations were developed and solved in this analysis to calculate the fraction of initial liquid mass removed by vacuum pumping.

Results of these calculations are presented in Figs. 7-1 and 7-2. These results agree reasonably well with values obtained using a technique of iterating between fluid state points, as presented in NBS Report 9189. The data presented in Figs. 7-1 and 7-2 are based on the following assumptions:

- Heat leak to the slush manufacturing dewar is zero. The analysis indicates that heat rates of less than 35.2 w (120 Btu/hr) will produce a negligible effect on the data presented.
- Initial liquid hydrogen saturation temperature is 20°K (36°R). Actual saturation temperature at the nominal SCTB environmental condition is 20.1°K (36.2°R).
- Vacuum pumping efficiency remains constant over the pressure range of interest, that is, from atmospheric pressure to 0.69 N/cm^2 (1 psia).

*During the second flow test, immediately prior to the transfer of each batch, the transfer line was rechilled by drawing a small quantity of liquid hydrogen from the storage dewar and flowing it into the test tank. This procedure also served to upgrade the quality of the stored slush, and to keep the transfer line and test tank chilled.

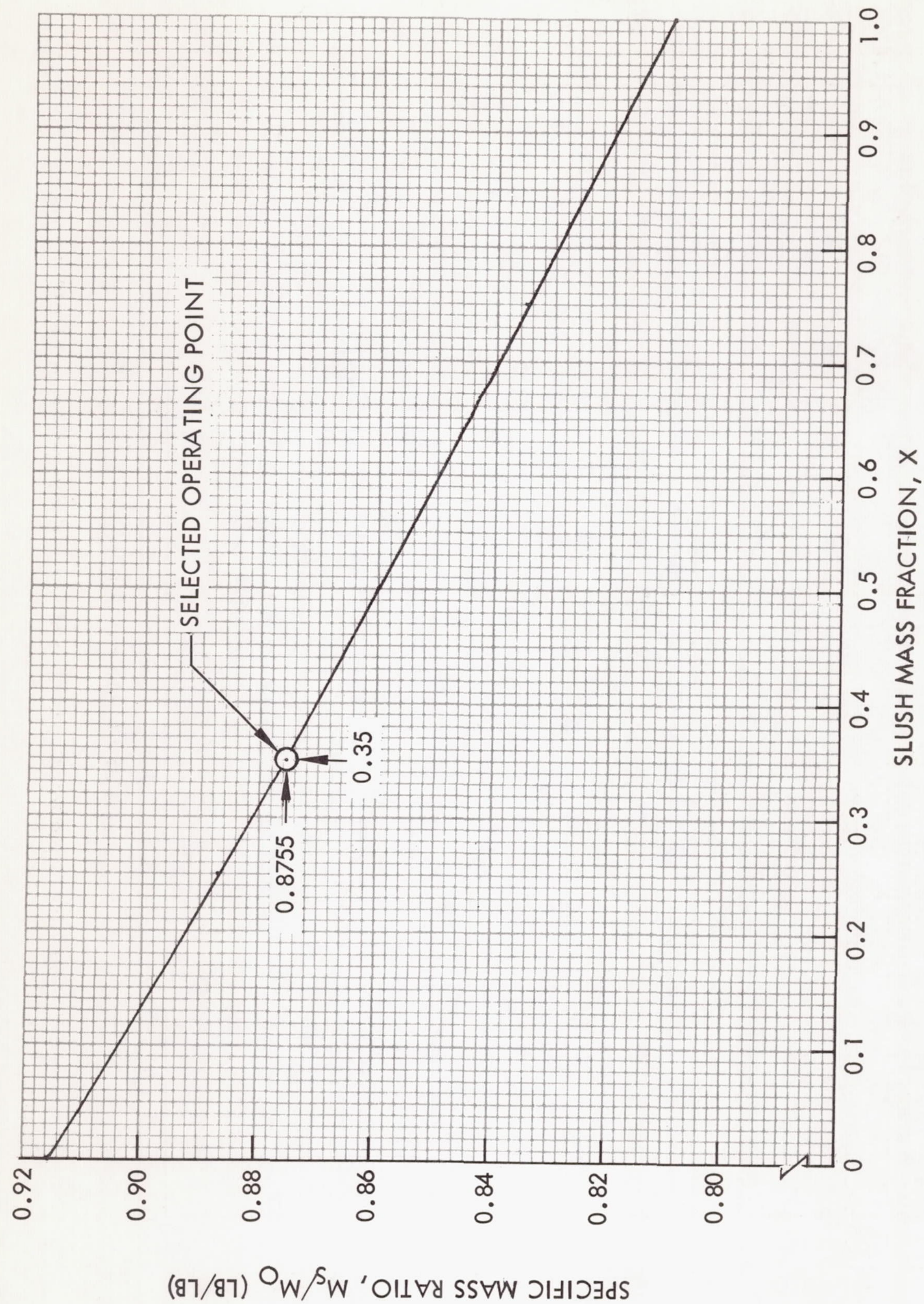

Fig. 7-1 Specific Mass Ratio for Production of Slush Hydrogen from Liquid Hydrogen Initially Saturated at 20°K (36°R)

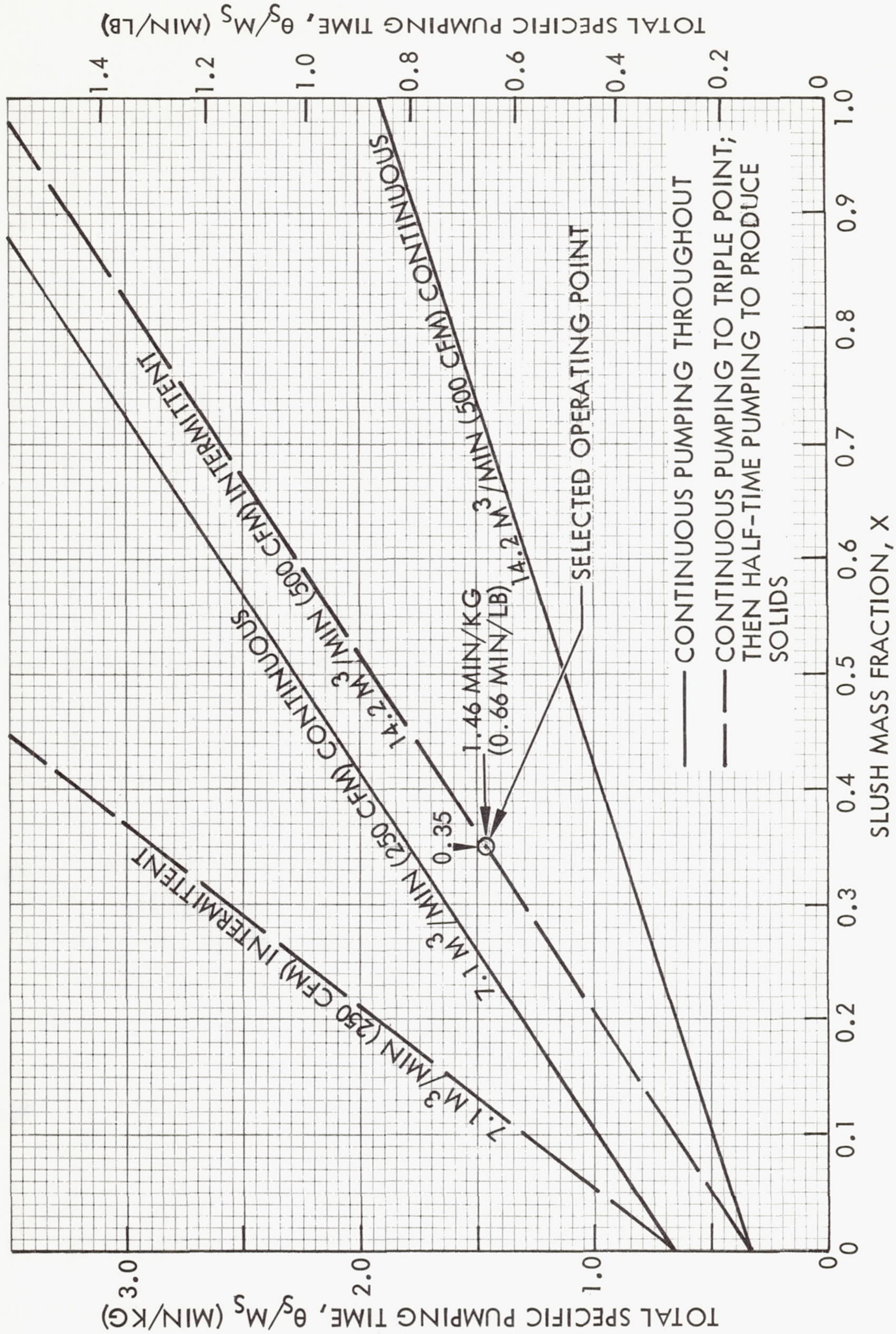

Fig. 7-2 Total Specific Pumping Time for Production of Slush Hydrogen from Liquid Hydrogen Initially Saturated at 20°K (36°R)

Figure 7-1 shows the ratio of final slush mass of any desired quality to the initial liquid mass saturated at 20°K (36°R). Figure 7-2 shows the total pumping time needed to produce one pound of slush of any desired quality. NBS experiments have indicated that the practical upper quality limit of freshly produced slush is about 35 to 40 percent, since the characteristics of the particles do not permit settling to greater solid fractions until after particle aging occurs. Figure 7-2 is based on continuous vacuum pumping between the initial saturation and triple-point conditions. Both one-pump operation at 7.1 m^3/min (250 cfm) and two-pump operation at 14.2 m^3/min (500 cfm) are shown. Figure 7-2 also shows results of continuous and intermittent vacuum pumping for one or two pumps during the production of solid at triple-point conditions. The intermittent pumping data are based on pumping for one-half the real time. NBS personnel have estimated this to be typical for the "freeze-thaw" process.

It was predicted prior to the first flow test that approximately 10.9 kg (24 lb) of 35 percent slush could be produced in 15.3 min if an initial liquid mass of 12.4 kg (27.4 lb) and the selected design point conditions indicated on Figs. 7-1 and 7-2 were assumed. This initial liquid mass was based on filling the production dewar to within 30.5 cm (12 in.) of the cover, which allowed 15.2 cm (6 in.) for the internal foam insulation plug and 6 in. for initial ullage. Due to the performance limitation of the manufacturing dewar vent gas heat exchanger (subsection 6.1), a range of probable pumping times was assumed in order to predict total manufacturing time and hydrogen requirements. The upper and lower limits of the assumed range were 35 min and 20 min, respectively. Further, a total transfer time of 10 min to initially fill the manufacturing dewar and to transfer the slush manufactured in each batch was assumed. The net manufacturing rate was thus predicted to be from 1.3 to 2.0 batches per hour. The actual average rate achieved during the first flow test was approximately 2.2 batches per hour.*

7.1.1.3 <u>Liquid and Slush Transfer Characteristics</u>. Transfer of liquid and slush hydrogen through the slush facility plumbing was accomplished throughout the test program using GHe pressurant precooled to LN_2 temperature. During the first and

*The average manufacturing rate that was achieved during the third test was approximately 3.0 batches per hour.

second flow tests, slush was transferred from the manufacturing dewar to the storage dewar, and subsequently from the storage dewar to the 105.4-cm (41.5-in.) diam test tank. During the third flow test, the slush was transferred directly from the manufacturing dewar to the test tank.

A comparison of analytically predicted and measured flow characteristics is presented in Fig. 7-3 for the particular section of transfer plumbing between the 3.04 m^3 (804-gal) storage dewar and the test tank. The analytic predictions shown apply to the finalized plumbing configurations, both before and after the modifications incorporated between the first and second flow tests.* Points that correspond to predicted flow requirements during steady-state groundhold recirculation, as well as data points that correspond to actual flow characteristics obtained from first and second flow test measurements, are indicated on Fig. 7-3. The analytically predicted flow characteristics are shown for atmospheric-saturated liquid, triplepoint liquid, and 50-percent slush hydrogen. It can be seen that the predicted pressure differentials for equal flow rates of slush compared to atmospheric-saturated liquid are slightly higher at low mass flow rates and slightly lower at high mass flow rates. This characteristic of the predicted values was based on results obtained by NBS personnel in the NBS slush-flow facility. All data points on the figure are well into the turbulent flow regime, since they correspond to Reynolds numbers ranging from approximately 1×10^5 to 2×10^6.

Analysis of the data presented in Fig. 7-3 shows that during the first flow test the average differential pressure between the storage dewar and the test tank was 3.92 N/cm^2 (5.69 psi) as the tank was initially filled. During one portion of the fill, approximately 30.3 kg (66.7 lb) of LH_2 were transferred into the tank in 253 sec. The mass flow rate that was achieved during this period was therefore approximately 0.120 kg/sec (0.264 lb/sec). The data shown for the second flow test were calculated in a similar manner. It can be seen that the predicted flow rate compared to the test data obtained during the first flow test was optimistic by approximately 15 percent at that particular

*The modification that primarily affected flow characteristics was the replacement of a section of flex line with a shorter hard-line elbow section (see Figs. 2-4 and 2-6).

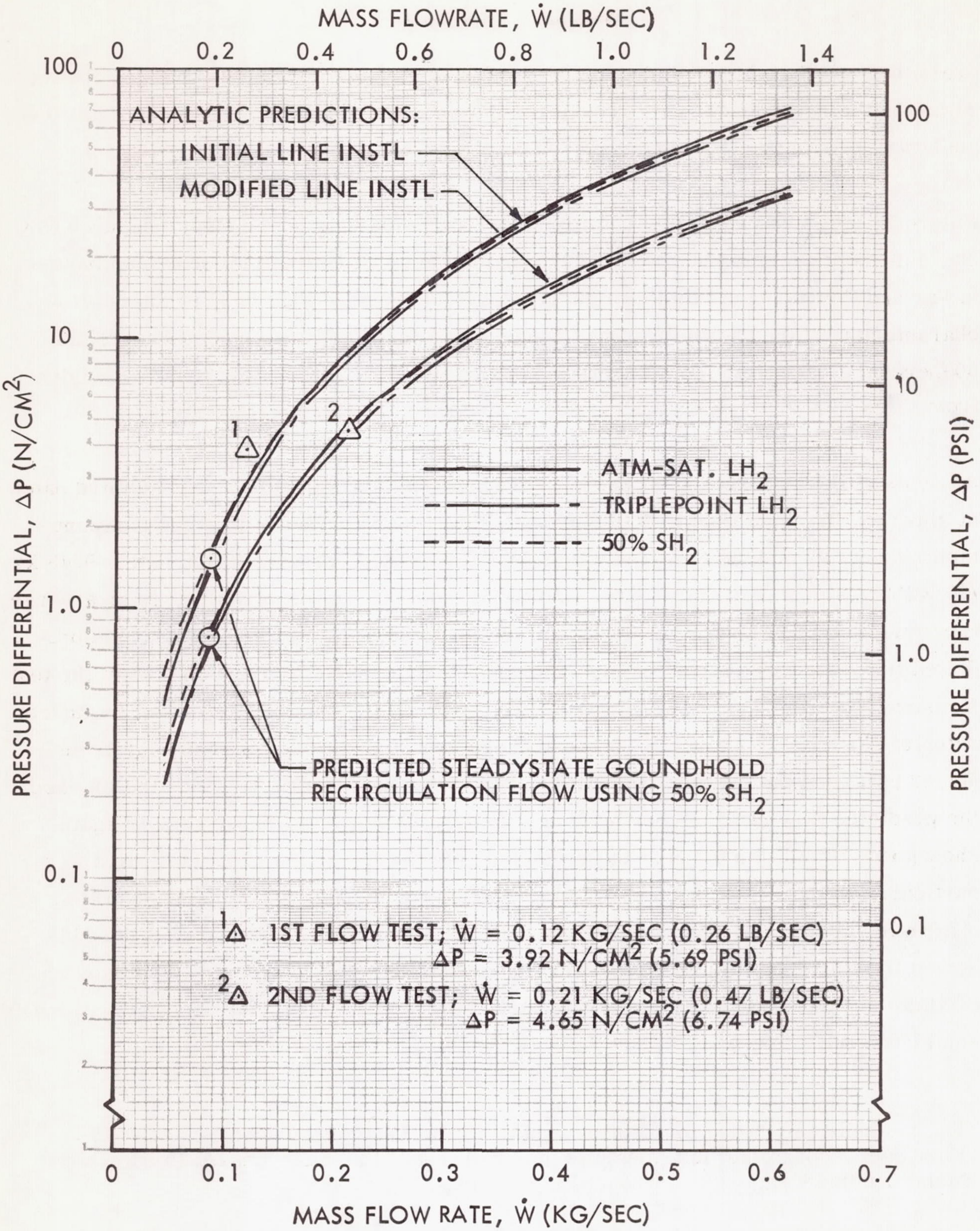

Fig. 7-3 Flow Characteristics for Slush Transfer Line Between 3.04-m^3 (804-gal) Storage Dewar and Test Tank

pressure, and that the predicted and measured flow rates were approximately the same for the second flow test. These results show good correlation between the analytical predictions and the measured test data.

Figure 7-4 presents a similar comparison of analytically predicted and measured flow characteristics for that section of the transfer plumbing between the manufacturing dewar and the test tank. In this figure, as was the case in Fig. 7-3, predicted flow characteristics are shown for atmospheric-saturated liquid, triplepoint liquid, and 50-percent slush. Data points that correspond to actual flow characteristics obtained from third flow test measurements are indicated on the figure.

Analysis of the data presented in Fig. 7-4 shows that during transfer of the third batch of slush for the third flow test, the average differential pressure between the manufacturing dewar and the test tank was 8.71 N/cm^2 (12.63 psi). Approximately 9.45 kg (20.8 lb) of slush were transferred into the tank in 34 seconds, resulting in an average flow rate of approximately 0.278 kg/sec (0.613 lb/sec). It can be seen that the predicted flow rate was approximately 15 percent higher than that calculated from the test measurements for this particular pressure differential. During transfer of the fourth batch of slush for this same test, the average pressure differential was 8.15 N/cm^2 (11.82 psi), and the average flow rate was 0.368 kg/sec (0.812 lb/sec). In this case, the predicted flow rate was low by approximately 19 percent. These results again show good correlation between the predicted and measured flow characteristics, particularly since the mass and time increments for these batch transfers were significantly smaller than for the first two flow tests thus magnifying the effects of inherent measurement tolerances. It is considered that the methods and data used to predict the flow characteristics for this test program* can therefore be used with good confidence for future work.

*The methods used were those presented in Crane Technical Paper No. 410, 1965. Flow data through the flex lines was obtained from "Pressure Losses in Flexible Metal Tubing," page 225, Product Engineering, April 1965.

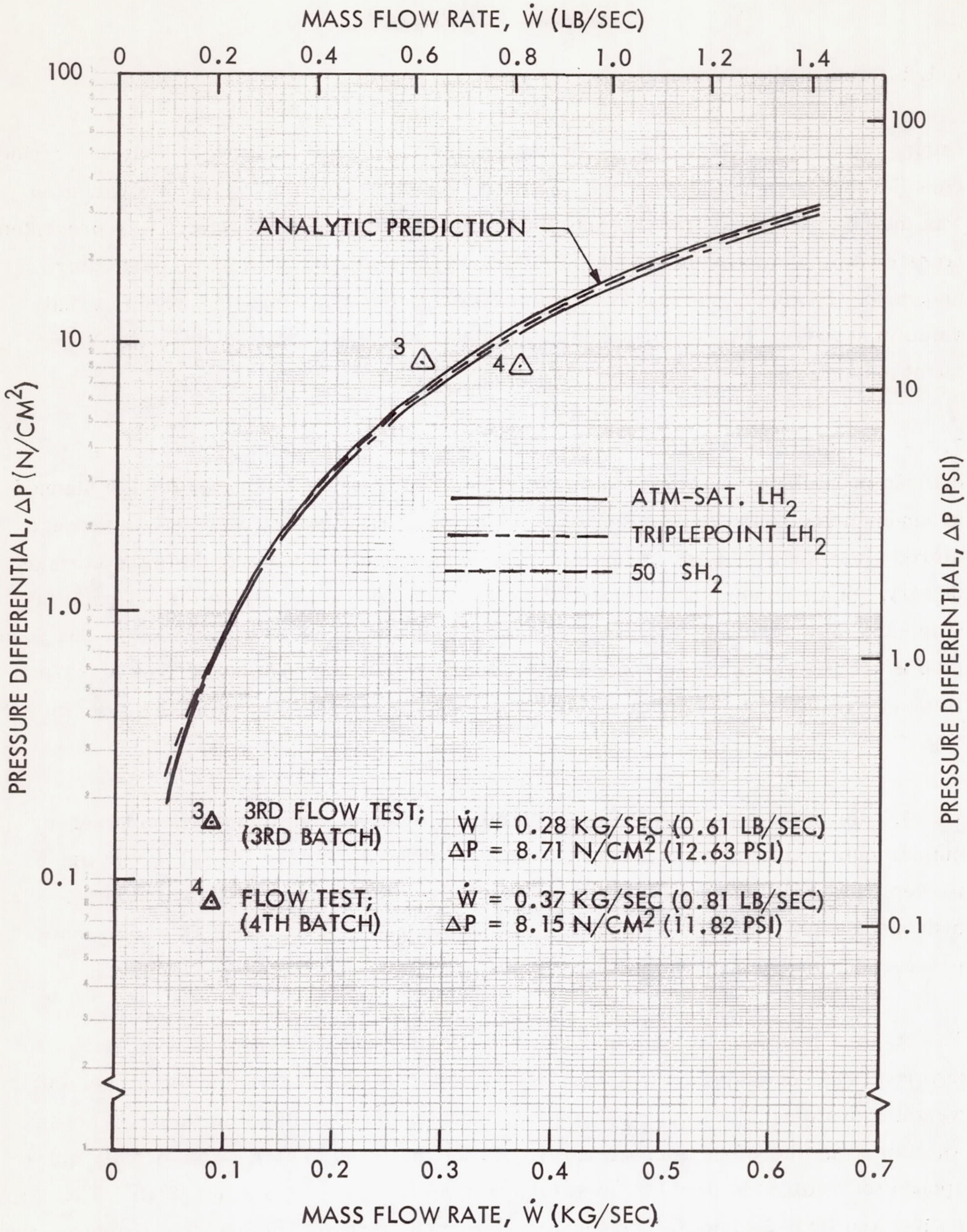

Fig. 7-4 Flow Characteristics for Slush Transfer Line Between Manufacturing Dewar and Test Tank

7.1.2 Groundhold Recirculation

During the first flow test, the recirculation flow parameters that were achieved varied considerably from those previously planned. The primary reason for this variation was the excessive heat transfer into the slush transfer line which effectively prevented transfer of any significant amount of solid into the test tank during this particular sequence. However, the experience and data obtained from this test were of great value in assessing the performance of system components and in planning the subsequent tests.

7.1.2.1 Planned Recirculation Test Parameters. The parameters that defined the desired propellant conditions and test apparatus environment selected for the planned groundhold recirculation test sequence during the first flow test were (1) an average stored slush quality of approximately 50 percent (resulting from aging in the storage dewar), (2) a vacuum chamber partial pressure of approximately 50 torr (1 psia) of GHe, and (3) a resulting simulated groundhold tank heat flux of approximately 631 w/m^2 (200 $Btu/hr\text{-}ft^2$) with a corresponding total heat rate of approximately 2452 w (8370 Btu/hr). A plot of the predicted flow characteristics versus test time is shown in Fig. 7-5.

7.1.2.2 Recirculation Test Results. Time histories of significant test tank sensor outputs obtained from reduction of the data recorded during the first flow test are presented in Figs. 7-6 and 7-7. Liquid and ullage temperatures, tank pressure, hydrogen weight, and liquid level data are shown in Fig. 7-6, while the liquid temperatures only are shown at a larger scale in Fig. 7-7.

The mass of hydrogen in the test tank when the OS-2 optical sensor was initially covered (290-sec elapsed time) was 31.0 kg (68.4 lb) as indicated by the propellant weighing system. The corresponding bulk density of the fluid below the OS-2 sensor waterline was therefore approximately 65.1 kg/m^3 (4.06 lb/ft^3). This density corresponds to a saturated liquid temperature of approximately 24.6°K (44.3°R). The RTB-1 and RTB-2 temperature sensors, however, indicated actual fluid temperatures

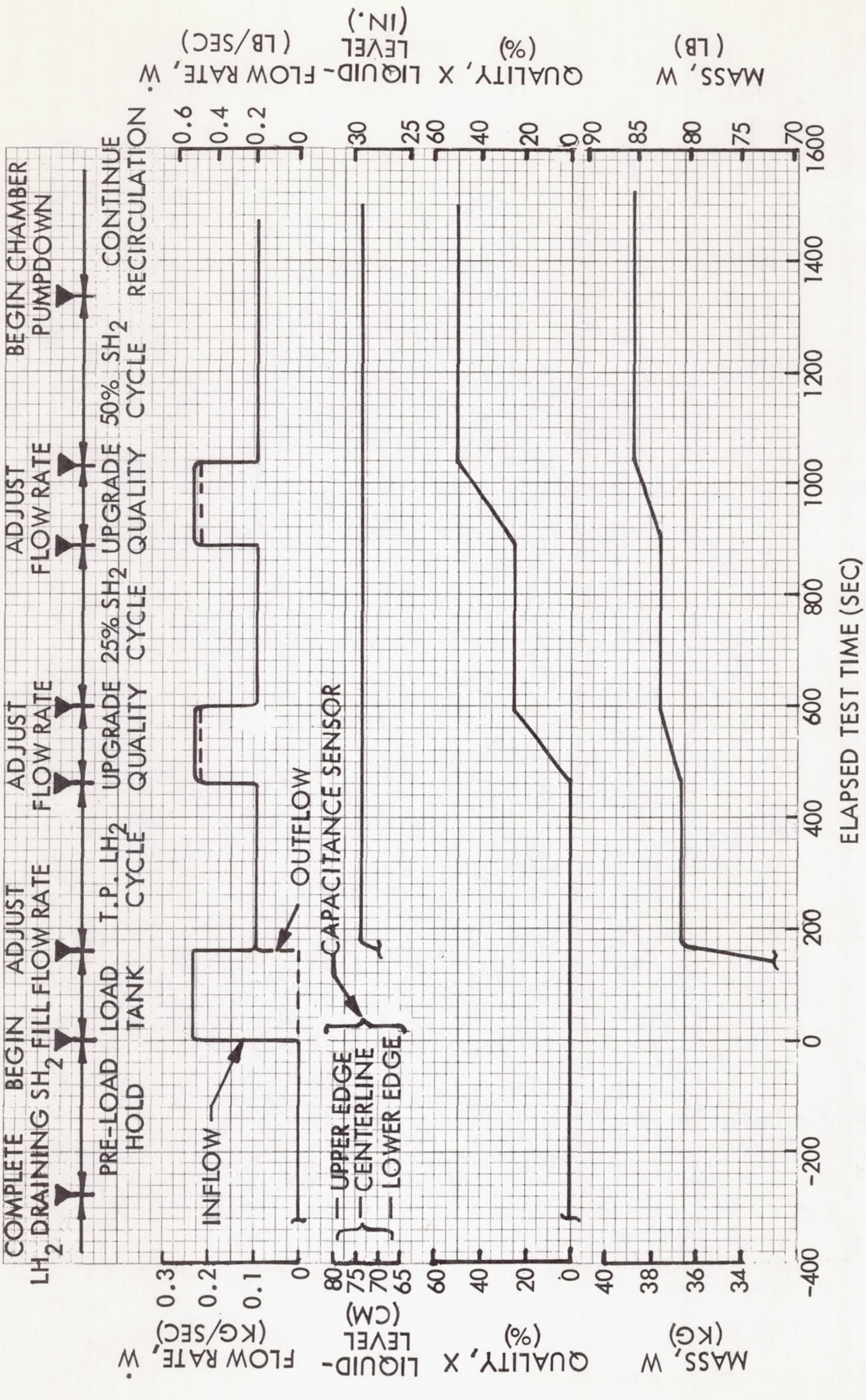

Fig. 7-5 Predicted Groundhold Recirculation Test Parameters

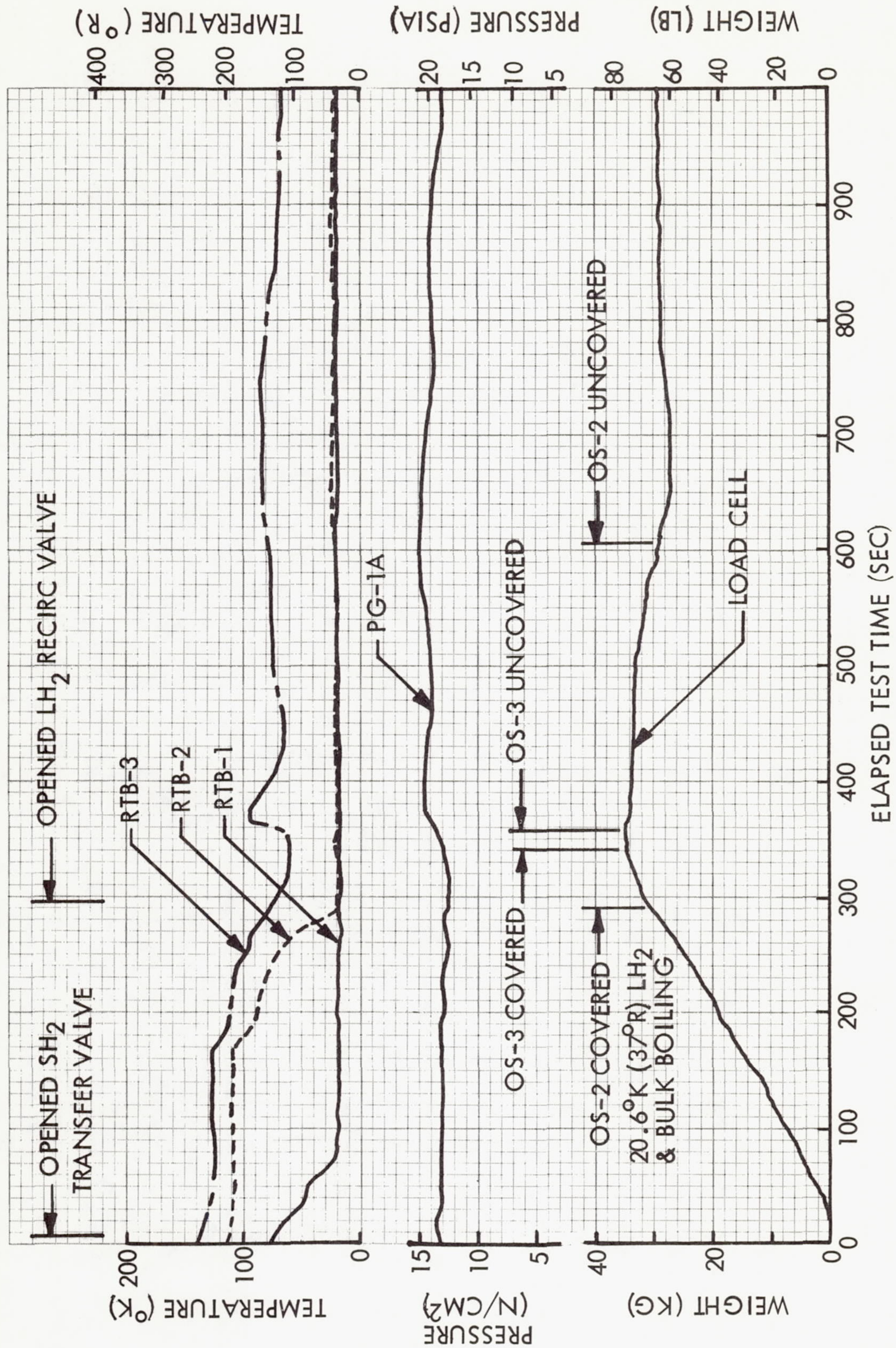

Fig. 7-6 Liquid Hydrogen Fill and Recirculation Data (First Flow Test)

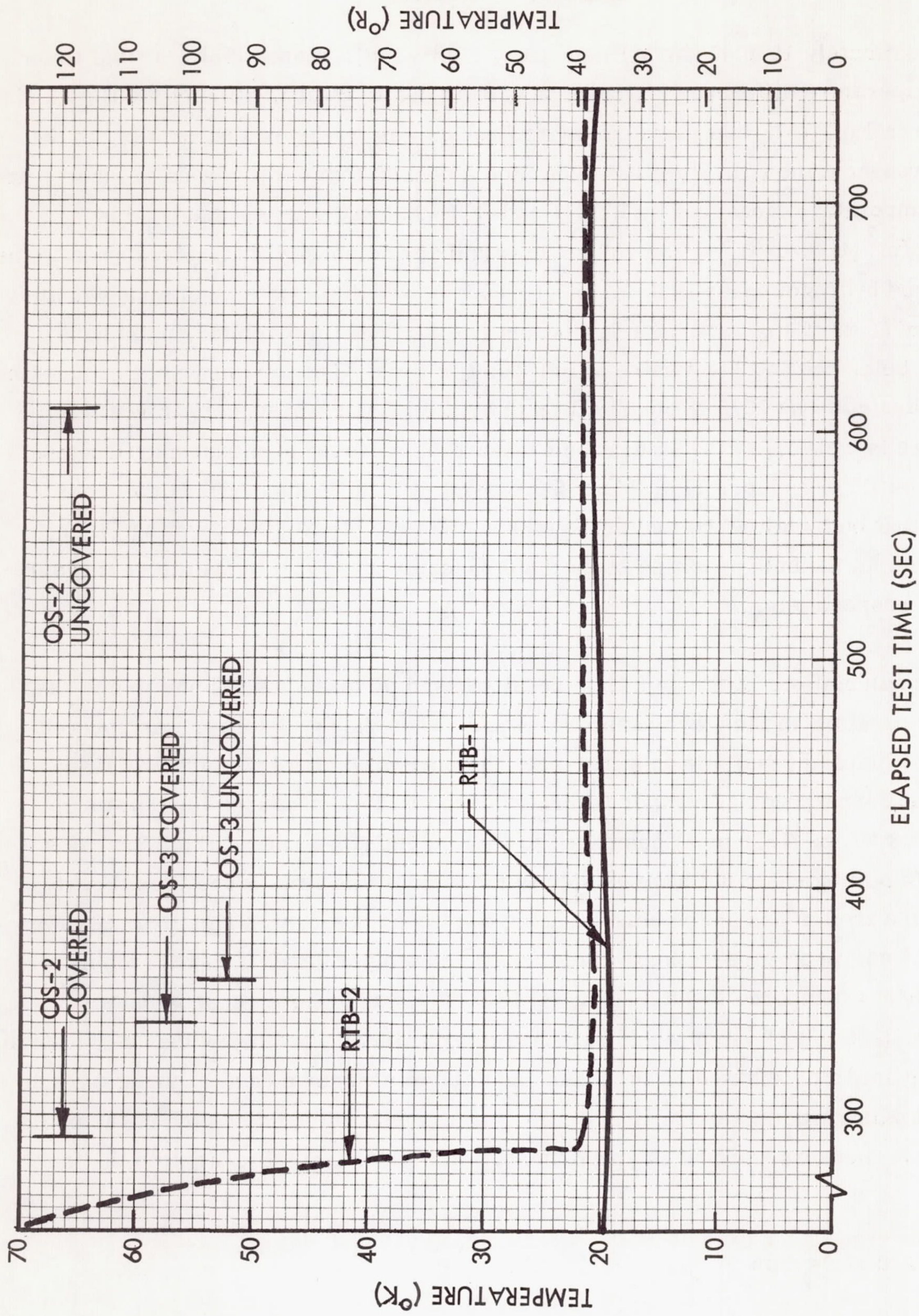

Fig. 7-7 Liquid Hydrogen Temperature Data (First Flow Test)

of approximately 19.6°K (35.3°R) and 21.5°K (38.7°R), respectively, at this time. The temperature difference of 1.9°K (3.4°R) is due to stratification of the fluid and, as seen in Fig. 7-7, this degree of stratification was typical of that existing in the tank throughout the first flow test. The liquid density that corresponds to the average fluid temperature measured by RTB-1 and RTB-2 at 290-sec elapsed time is 70.4 kg/m^3 (4.40 lb/ft^3). The volume of liquid at this density that corresponds to the measured hydrogen mass is 0.441 m^3 (15.56 ft^3), which indicates that approximately 0.037 m^3 (1.29 ft^3) of vapor, or 7.7 percent of the total fluid volume, must have existed below the OS-2 waterline at this point in time. The tank pressure at this time was indicated to be 12.5 N/cm^2 (18.1 psia) by the PG-1A transducer. Since this pressure is well below the saturation pressure of hydrogen at the measured temperature from RTB-2, i.e., 14.3 N/cm^2 (20.8 psia) at 21.5°K (38.7°R), it was concluded that bulk boiling existed in the tank at the time, thereby accounting for the difference in the bulk densities of the fluid based on mass and temperature measurements, respectively.

Similar calculations of the bulk fluid density based on mass and volume in one case, and temperature in the other case, were made when the OS-3 sensor was covered (340-sec elapsed time). In this instance, the measured tank pressure was higher than that corresponding to vapor saturated at the RTB-2 measured temperature, i.e. 12.8 N/cm^2 (18.6 psia) compared to 11.2 N/cm^2 (16.2 psia), which indicates that bulk boiling could not have existed in the tank at this time. The fluid density calculated from mass and volume measurements, however, was significantly lower than that corresponding to the average measured temperature, i.e. 62.7 kg/m^3 (3.91 lb/ft^3) compared to 71.0 kg/m^3 (4.43 lb/ft^3). Therefore, approximately 0.065 m^3 (2.3 ft^3) of vapor would have had to exist in the fluid below the OS-3 waterline at this point in time based on the mass and volume measurements. During the subsequent data reduction and analysis phase, it was determined that each of the optical point level sensors introduces approximately 4.5 watts (15.3 Btu/hr) into the tank*.

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*Manufacturer's data.

Since the OS-2 sensor was operative at the time the OS-3 sensor was covered, it was concluded that a column of vapor could have formed in the liquid above the OS-2 sensor due to this high heat flux and could have significantly disturbed the liquid-vapor interface in the vicinity of the OS-3 sensor, which is located 11.4 cm (4.5 in.) directly above the OS-2 sensor. In any case, the fluid volume indicated by the OS-3 sensor is considered to be questionable, and the density corresponding to the average measured temperature is considered to be approximately correct for this particular data point.

7.2 SECOND SLUSH FLOW TEST

Subsequent to the performance of the first slush flow test, a detailed review of the program was conducted to determine (1) exactly what had physically occurred during the first flow test, and (2) what could then be done to modify the facility and/or test procedures to successfully complete the program. It was found that severe thermal oscillations had occurred in slush transfer line bayonet fittings and valve stems during the test. The possibility of the occurrence of such oscillations, and the high heat transfer that would result from them, were factors that were considered during the design and procurement of the transfer line components.* It was knowledge of these factors that had dictated selection of bayonet fittings designed with cold nose seals and valves with close-tolerance extended stems. It was clear from the results of the first test, however, that the true scaling effects for a facility of this size were not previously known, and that the hardware designs selected did not satisfy the stringent requirements imposed by transfer of triple-point hydrogen.

Review of details of the first flow test revealed that the highest heat flux resulting from the thermal oscillations had occurred at particular bayonet fittings where frost formed on the outer surfaces in the vicinity of the clamped joints after transfer of a relatively large quantity of slush hydrogen. This had not occurred during the preliminary slush manufacturing and transfer tests, nor during numerous tests involving transfer of large quantities of liquid hydrogen. One of the bayonets where the heat

*NBS personnel consulted during the early phase of the program had previously observed the thermal oscillation phenomena in a bayonet fitting that did not have a cold nose seal or close physical tolerances, as well as in valves.

leak had been highest was disassembled and inspected after the flow test. No damage or discrepancy in the physical appearance of the bayonet or the cold nose seal could be found. It was then concluded that the most probable cause of the oscillation was the basic design of the nose seals per se. These seals were fabricated from Teflon and are split at one point on the periphery to permit installation into a groove at the cold end of the male fitting. The design dimensions of the seal are such that the butt joint formed where the seal is split will normally be pre-loaded in compression as the fitting is mated. The design preload is intended to provide a close fit, even after contraction of the seal (which is greater than that of the stainless-steel fittings) as the system is chilled to slush hydrogen temperature. It was determined during the post-test review that varying amounts of force had been required to seat each of the bayonets in the system during the initial installation. This fact suggests that the dimensional tolerances of the fittings and seals as fabricated could have resulted in insufficient compression preload on some of the seals when installed at ambient temperature so that a slight gap could have been formed at the butt joint during chill-down. In any case, this test result is of significance since it proves that hardware designs and quality control must be improved for slush hydrogen service over those that are currently considered state-of-the-art for liquid hydrogen service.

It is considered that detailed design and experimental studies should be undertaken to find a solution to the problem of transfer-line design and thermal performance for future test and vehicle installations. During such studies, bayonet fittings suitable for slush hydrogen service should be developed, if possible, since their use increases system flexibility for installation, maintenance, and repairs, thereby reducing costs. With regard to bayonets in particular, a new type of cold-nose seal for existing designs as well as completely new designs should be studied. Since a significant portion of the total heat rate into any given transfer line system is through the bayonet fittings,*

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*For example, approximately 20 percent of the total heat rate predicted for the Lockheed slush transfer line between the storage dewar and the test tank is that attributed to the bayonet fittings (based on manufacturer's data for nominal heat transfer through each component of the system).

alternate system designs without bayonets should also be considered in these studies. Possible design candidates for which thermal performance and cost tradeoff data should be generated and evaluated include (1) all-welded vacuum-insulated plumbing where the slush supply and liquid recirculation lines are separate, (2) all-welded multi-axial plumbing where the slush supply line is vacuum-insulated and integrated with a larger diameter, concentric, vacuum-insulated liquid recirculation line, and (3) alternates to (1) and (2) above where the lines are designed and fabricated in sections using separate clamped or bolted joints with suitable seals provided in both the inner line and the outer concentric line and/or vacuum jacket(s).

Discussions with NBS personnel subsequent to the first flow test revealed that a relatively simple modification of the slush transfer valves could be made to prevent thermal oscillations in these components. In a particular test at the NBS slush flow facility, such a modified valve was used with excellent results. The modification consisted of installing a simple square-section seal, provided with a staggered butt joint, into a groove on the valve stem, so that a close tolerance fit was maintained between the seal and the stem guide when the valve was chilled to slush temperature

During the program review, it was determined that a number of relatively simple modifications to the facility and to the operating procedures would significantly improve the system performance and permit successful completion of the program. The hardware modifications that were subsequently carried out are described in Section 2.1.3. Figures 2-5 and 2-6 show the modified facility. The procedural changes, and the results of the second slush flow test are discussed in this section.

7.2.1 Test Procedure Modifications

In addition to the facility modifications discussed in Section 2.1.3, the following actions were also taken, prior to initiation of the second slush flow test:

(1) The test plan was reoriented to provide a sequence that would maximize test results. The modified sequence included* (a) initial tank loading

*During the second flow test (a) and (b) were accomplished, but (c) and (d) were not because of the continued high heat loads on the transfer plumbing.

and performance of a recirculation test with the vacuum chamber pumped to a pressure of 1.0×10^{-5} torr or lower, (b) performance of orbit storability and draining tests with the initially loaded slush, (c) reloading of the tank and performance of a groundhold recirculation test with the vacuum chamber pressurized to 50 torr with GHe, and (d) performance of an ascent storability test.

(2) All vacuum-jacketed transfer line sections were checked and pumped to a vacuum pressure of approximately 1.0×10^{-5} torr.

During the second slush flow test, slush manufacturing, transfer, and storage procedures were modified as follows:

(1) After prechilling of the manufacturing dewar, storage dewar, transfer line, and test tank with liquid hydrogen, the test tank ullage space was vacuum-pumped to maintain approximately 3.4 N/cm^2 (5 psia) of pressure throughout the manufacturing/storage cycle.

(2) During the manufacture of each batch of slush, the storage dewar and the manufacturing dewar were isolated from the transfer line; the line, however, was opened to the test tank and kept partially chilled by liquid from the test tank.

(3) Immediately prior to transfer of each batch of slush to the storage dewar, the transfer line was rechilled by withdrawing a small amount of liquid from the storage dewar screened line and flowing it into the test tank.

(4) Approximately every 10 batches, the manufacturing dewar was refilled with subcooled liquid from the storage dewar to upgrade the quality of stored slush.

(5) Prior to all pressure transfer operations, a small amount of GHe was vented through bleed valves near the manufacturing and storage dewar pressurant inlets to ensure that only LN_2 temperature pressurant was introduced for transfer.

(6) After storage dewar filling and upgrading operations were completed, a partial batch of slush was transferred into the manufacturing dewar for visual inspection through the windows to ensure that the storage dewar did in fact contain slush.*

(7) During the slush manufacture and storage cycle, an attempt was made to keep the liquid recirculation line between the shutoff valve outside of the vacuum chamber and the truck dewar chilled with liquid hydrogen in the truck dewar.**

7.2.2 Slush Manufacture, Transfer, and Storage

During performance of the second slush flow test, the modified procedures described in the previous section were carried out with excellent results. A total of 66 batches of slush were manufactured and transferred for this test. As noted in Section 2.1.3, the use of foam insulation around the exterior surfaces of the bayonet fittings was found to be unacceptable because it reduced the resiliency of the Butadiene O-ring seals so that leakage resulted. The insulation was removed and no further leakage occurred.

7.2.3 Test Results

Time histories of significant test tank sensor outputs obtained from reduction of the data recorded during the second slush flow test are presented in Fig. 7-8. Liquid and ullage temperatures, tank pressure, hydrogen weight, and liquid-level data are again shown as for the first test.

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*The quality of the slush thus observed through the window was estimated to be between 10 and 20 percent.

**During the test, it was found that this was not effective; the relatively warm line again resulted in choked flow and difficulty was experienced in liquid-level control in the tank.

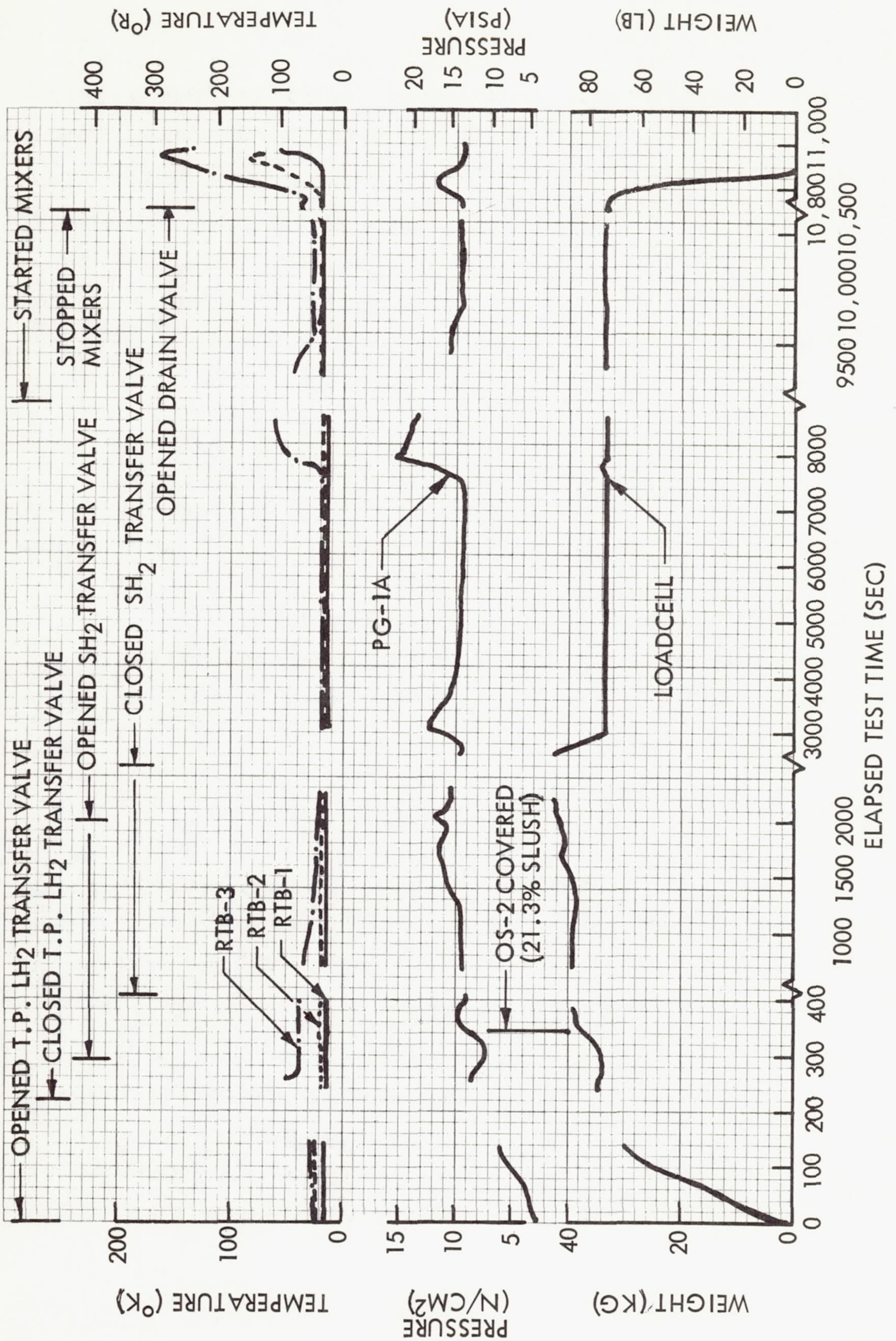

Fig. 7-8 Slush Hydrogen Fill, Recirculation, and Storability Data (Second Flow Test)

The bulk density of the hydrogen in the tank when the OS-2 optical sensor was initially covered (341-sec elapsed time) was calculated to be approximately 78.899 kg/m^3 (4.925 lb/ft^3). This density corresponds to a slush quality of 21.3 percent. The RTB-1 temperature sensor located at the 13.6-percent waterline indicated a temperature of approximately 15.6°K (28.0°R) at this time. It is considered, however, that the uncertainty in this temperature reading (see discussion in Section 5.4) could account for the fact that triple-point temperature was not indicated. It should also be noted from comparison of the relative locations of RTB-1 and the slush fill baffle (see Fig. 3-6 and Table 3-1) that the RTB-1 sensor was probably not covered with slush at this time. The RTB-2 temperature sensor reading at the time OS-2 was covered was approximately 18.0°K (32.3°R), which indicates a temperature differential of approximately 2.4°K (4.3°R) due to thermal stratification in the tank.

No other discrete volume data points could be determined from the recorded data. However, it can be seen by inspection of the weighing system time history that the weight of hydrogen loaded into the tank increased significantly after the OS-2 sensor was covered, but without the OS-3 sensor being covered. Therefore, it is considered that somewhat higher slush qualities could have existed in the tank between 340 sec and 2200 sec of elapsed time. Unfortunately, the exact qualities cannot be determined accurately since the liquid level could not be controlled to the desired waterline (see discussion in Section 7.2.1).

Further inspection of the data shown in Fig. 7-8 shows that during the space storability test, hydrogen temperatures and pressures remained approximately constant, even without mixing, until rapid repressurization of the vacuum chamber due to momentary recurrence of a "cold leak" (see Section 6.6) caused the ullage temperature and pressure to rise sharply. The chamber was re-evacuated and no further leakage occurred.

Pressure and temperature time histories from measurements within the fluid in the tank during operation of the mixers is shown in Fig. 7-9. It can be seen by inspection of these data that no solid existed in the tank during the mixing cycle, thus the pressure

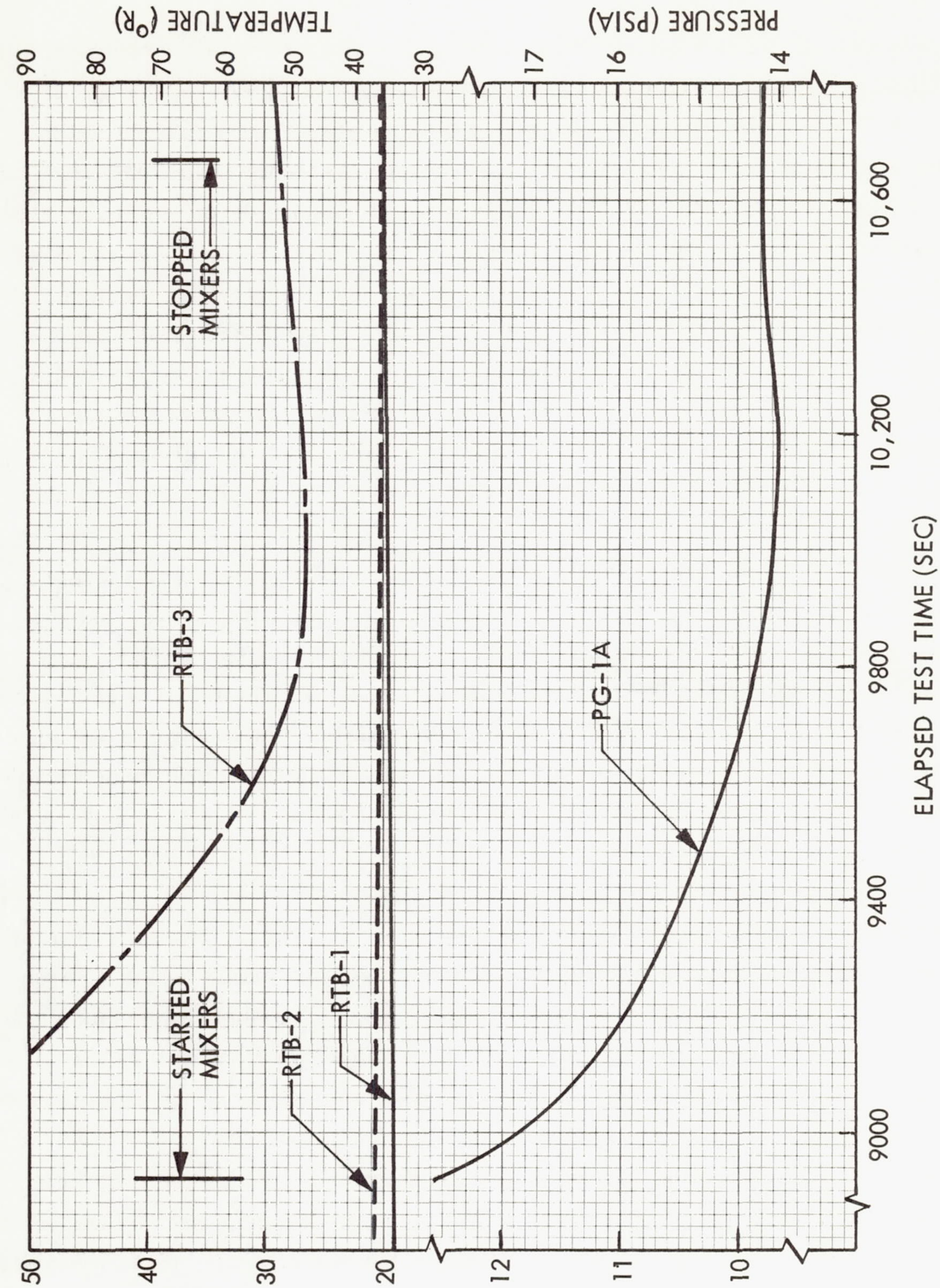

Fig. 7-9 Liquid Hydrogen Temperatures and Pressures During Mixing (Second Flow Test)

was never collapsed to near the triplepoint pressure. However, the ullage gas temperature and pressure were reduced significantly during the first 1000 sec of mixing. For example, ullage pressure was reduced from approximately 12.6 N/cm^2 (18.3 psia) to approximately 9.7 N/cm^2 (14.1 psia) during this period. Saturation pressure corresponding to the measured liquid temperature of approximately 19.8°K (35.6°R) at an elapsed test time of 10,002 sec is 8.7 N/cm^2 (12.6 psia). Therefore, mixing reduced the ullage pressure to within approximately 1.0 N/cm^2 (1.5 psia) of the saturation vapor pressure of the liquid in the tank. This demonstrates that mechanical mixing is an effective way to control tank pressure, at least for liquid hydrogen. It is of considerable significance also to note that the optical sensors were not activated during this mixing test and, therefore, did not affect the temperatures and pressures of the fluid. The high heat flux introduced into the ullage gas by these sensors during the third flow test did significantly affect the results obtained by mixing (see subsection 7.3.3).

Tank sensor outputs shown in Fig. 7-8 for the draining test performed at the end of the simulated space storability test sequence are shown in greater detail in Fig. 7-10. It can be seen from this data that the drainline temperature was relatively high as the valve was opened to simulate an engine firing. The mass flowrate through the drainline increased very slowly for the first 50 sec as the line was chilled, and then increased rapidly as the tank emptied. The increased flowrate indicated by the flowmeter data near the time when the tank was emptied was apparently due to two-phase flow and should be disregarded. It is considered that no solids existed in the tank at the initiation of draining. The differential pressure that was imposed between the tank and the drainline pressure sensor was approximately 0.6 N/cm^2 (1.0 psi).

7.3 THIRD SLUSH FLOW TEST

The final results of the first and second slush flow tests could not be determined without complete reduction and evaluation of the recorded data. However, a preliminary data evaluation indicated that a post-test recalibration of platinum resistance thermometers located in the test tank during the tests would be necessary (see Section 5.4).

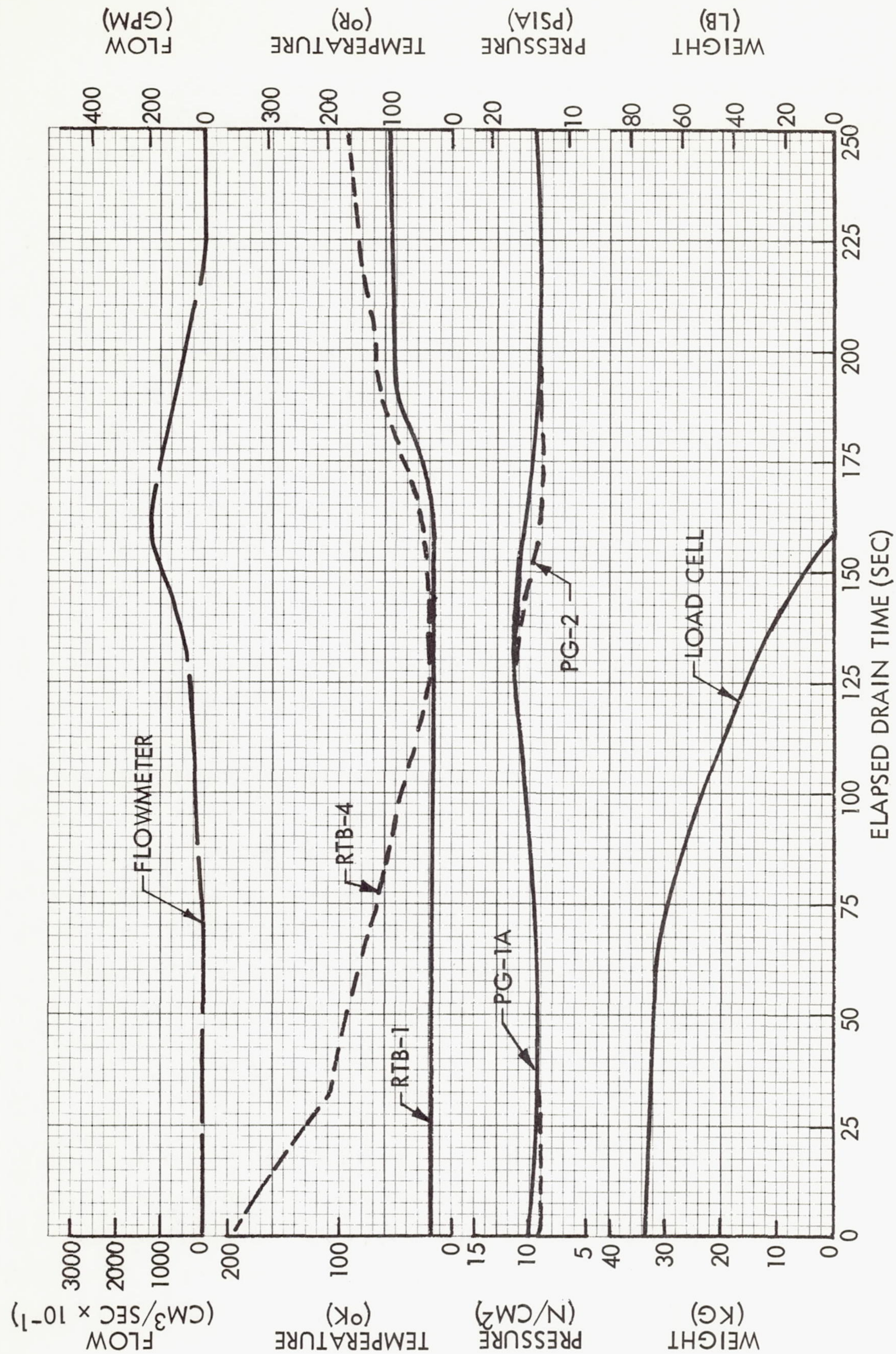

Fig. 7-10 Liquid Hydrogen Drain Data (Second Flow Test)

Since this would require partial disassembly of the test apparatus, it was decided to conduct a third slush flow test prior to partial disassembly of the apparatus.

A thorough review of the results of the first two tests was conducted to determine what facility and procedural modifications would maximize the test results. Analyses were performed to determine what the actual heat leak into the transfer line might be, and what slush quality degradation would result from this heat leak. Equation (2.3) from Lockheed Report K-11-67-1, Vol. II, shows the relationship between quality degradation in a transfer line and the relative heat loads on the line and the receiving tank during steady-state recirculation flow to be

$$\frac{\Delta X}{X_1} = \frac{1}{1 + \frac{Q}{Q'}}$$

where

ΔX = slush quality degradation due to heat leakage into the transfer line

X_1 = slush quality at the inlet to the line from the slush storage dewar (35 to 50 percent nominally)

Q = steady state groundhold heat load on the receiver tank = 2452 w (8370 Btu/hr)

Q' = steady-state heat load on the transfer line

An estimate of the heat load for the section of transfer line between the storage dewar and the test tank, based on the manufacturer's quoted performance with no thermal oscillations is approximately 55.7 w (190 Btu/hr). It was estimated that the effect of thermal oscillations at bayonet fittings and valves could result in an order of magnitude or greater increase in this heat load. Solution of the above equation, assuming these two limits in line heat load, shows that the quality degradation in the line would be approximately 2 percent for the nominal heat load, and approximately 19 percent for the order of magnitude higher heat load. These degradation values would decrease if the flow rate were increased above that required for steady-state recirculation.

Based on this analysis, and the uncertainty in the effect of transfer line thermal oscillations on the storage dewar heat load, it was decided to transfer slush directly into the test tank from the manufacturing dewar for this flow test.

7.3.1 Test Procedure Modifications

Three procedural modifications were made in planning the third flow test, in addition to the decision to transfer slush directly from the manufacturing dewar into the test tank. The first was to elevate the front of the truck liquid receiver dewar approximately 0.610 m (2 ft). This was done to prevent vapor formation in a built-in vapor trap in the dewar fill and drain line so that the line could be kept completely chilled with liquid hydrogen from the truck dewar prior to initiating recirculation flow. The second modification was to keep the test tank drain line completely empty prior to and during the test in an effort to control the vacuum chamber "cold leak" and to prevent inadvertent chamber pressurization. The third modification in procedure was to conduct the test with the chamber initially vacuum-pumped to a pressure of 1.0×10^{-3} torr so that the vacuum roughing pumps and the associated high-vacuum pumping system blower could be used to repump the chamber between manufacture of each batch. Continuous vacuum pumping could not be provided since the roughing pumps were also used to manufacture slush, and pumping below the 1.0×10^{-3} torr pressure could not be accomplished because the warmup cycle for the high-vacuum diffusion pumps is approximately 45 min.

The slush transfer line between the manufacturing dewar and the test tank was isolated after each transfer operation and kept partially chilled with liquid hydrogen contained in the storage dewar.

7.3.2 Slush Manufacture and Transfer

During the third flow test, the procedure modifications discussed in the preceding section were carried out with excellent results, except that the vacuum chamber pressure increased to approximately 8.0×10^{-3} torr during each manufacturing cycle.

This resulted in somewhat higher melting rates than had been planned. The range of heat load on the tank for this range of vacuum chamber pressure is approximately 20.5–35.2 w (70 – 120 Btu/hr).

A total of 10 batches of slush were manufactured and transferred in approximately 3 hours and 20 minutes.

During the third test, no difficulty was experienced in initiating flow from the test tank into the truck receiver. This indicated that the attempt to prechill the line was successful. In an effort to minimize melting of the solids transferred into the tank, no GHe pressurant was introduced into the tank during the test. Recirculation flow to the truck dewar was accomplished using hydrogen ullage vapor pressure only from the fifth through the tenth batch transfers.

7.3.3 Test Results

Significant test tank sensor outputs obtained from reduction of data recording during the third slush flow test are presented as a function of elapsed test time in Figs. 7-11 and 7-12. Data is shown for slush and ullage temperatures, tank pressure, hydrogen weight, and liquid level at discrete points where optical sensors were just covered or uncovered by the liquid-vapor interface.

The bulk density of the hydrogen in the tank when the OS-2 sensor was initially covered (during the fourth batch transfer; 3695 sec elapsed time) was calculated to be approximately 74.27 kg/m^3 (4.636 lb/ft^3). This density corresponds to a saturated liquid temperature of approximately 17.1°K (30.7°R). The RTB-1 and RTB-2 temperature sensors indicated liquid temperatures of approximately 16.1°K (29°R) and 16.7°K (30°R), respectively, at that time. These temperatures are well within the uncertainties due to thermoelectric and other effects (see Section 5.4).

From the fourth through the tenth batch transfers, the liquid level remained between the OS-2 and OS-3 sensors. Typically, the weight of hydrogen in the tank during this

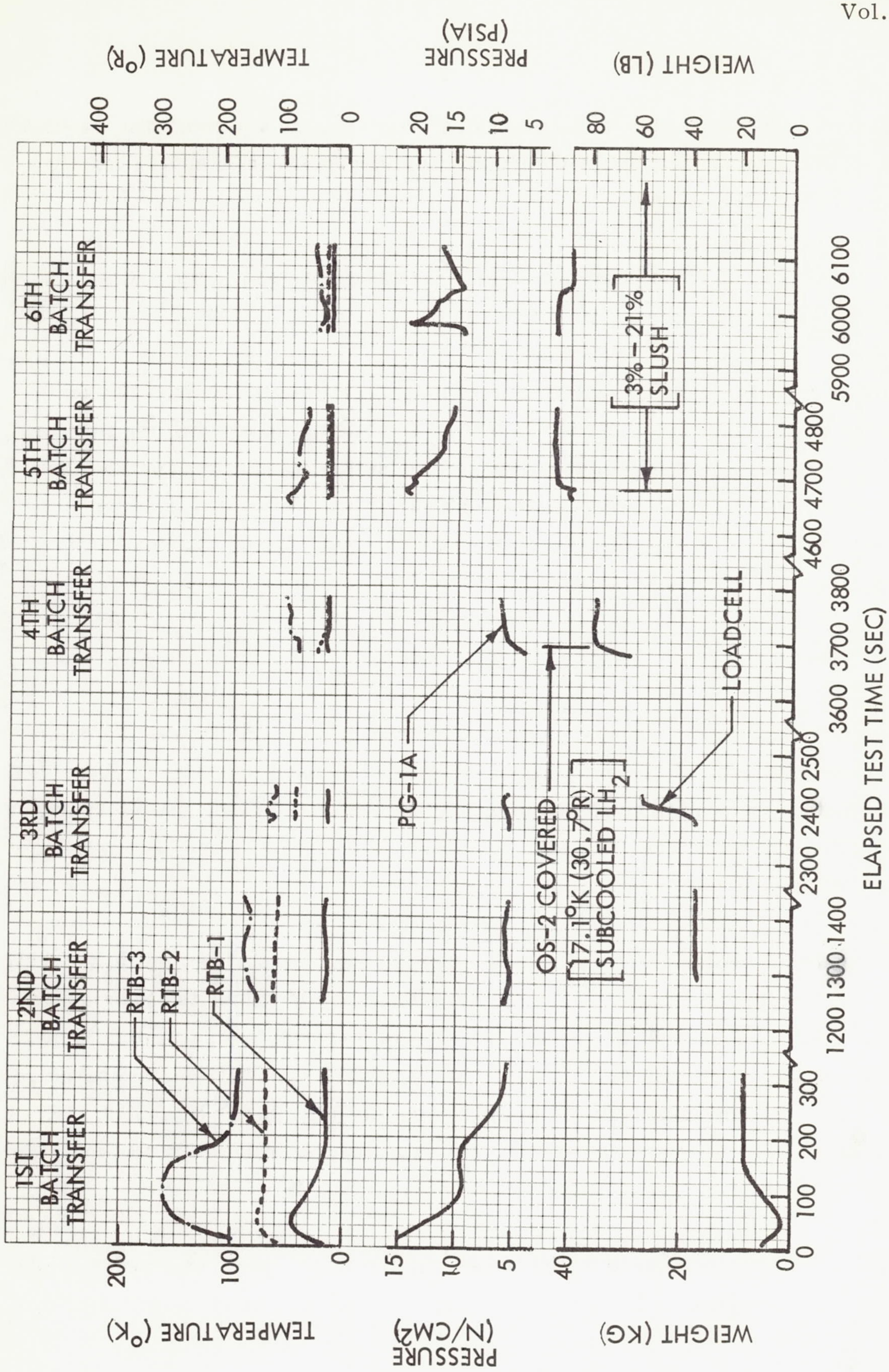

Fig. 7-11 Slush Hydrogen Fill and Recirculation Data (Third Flow Test)

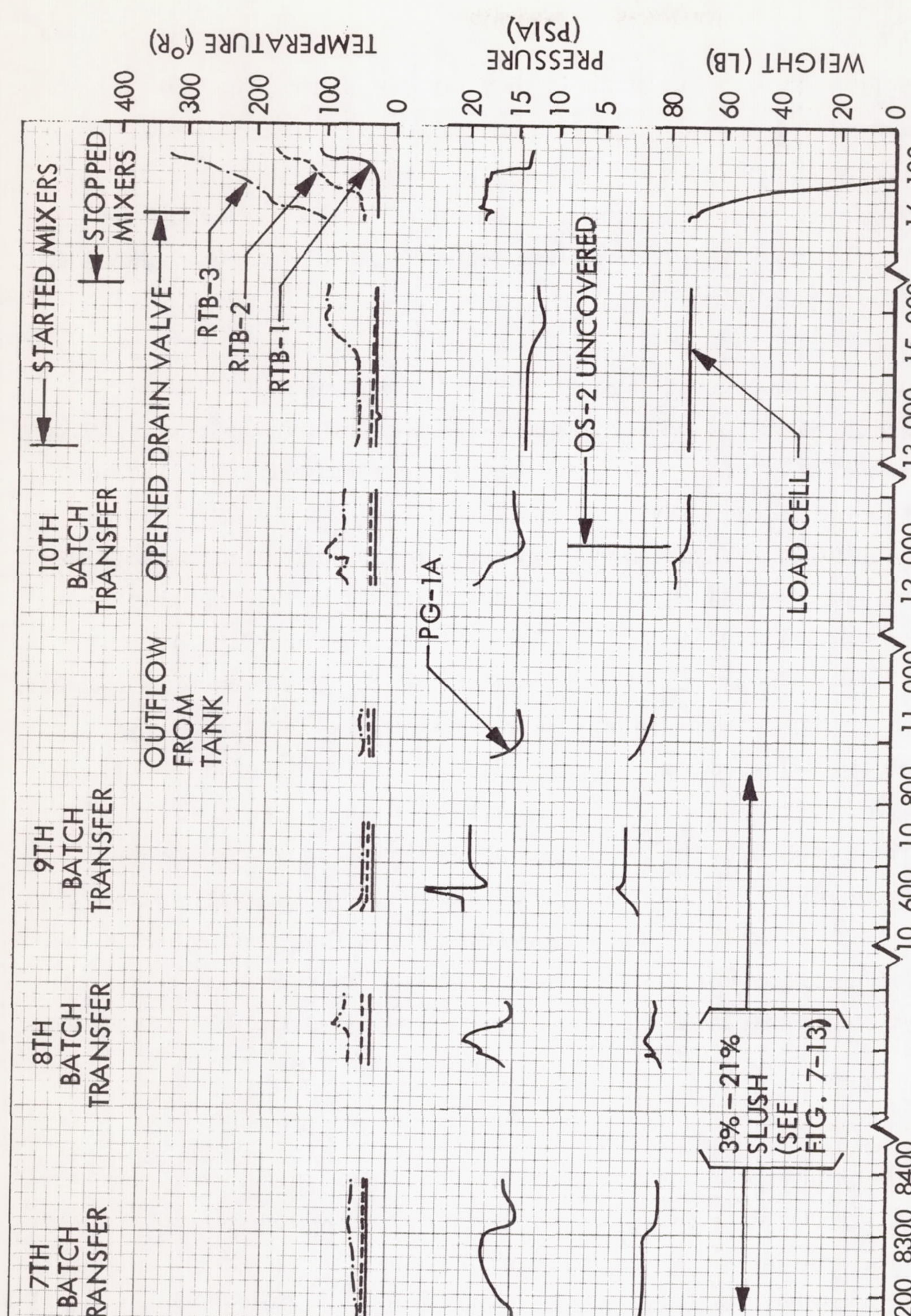

Fig. 7-12 Slush Hydrogen Recirculation and Storability Data (Third Flow Test)

period ranged from 37 to 43 kg (82 to 95 lb) as shown in Fig. 7-13. The slush quality calculated for a number of data points during this interval, conservatively using the volume corresponding to the OS-3 sensor (although the data indicates that it was never covered), ranges from approximately 3 to approximately 21 percent. It is apparent, therefore, that somewhat higher slush qualities actually existed in the tank at discrete times during the interval.

When the OS-2 sensor was uncovered during the tenth batch transfer (12,010 sec of elapsed time), the bulk density of the fluid below the sensor waterline was calculated to be approximately 69.78 kg/m^3 (4.356 lb/ft^3) based on measured mass and volume. This density corresponds to liquid saturated at approximately 21.1°K (38.0°R). However, the tank ullage temperature sensor indicated that a significant increase in heat load on the tank occurred subsequent to the ninth batch transfer. The RTB-1 and RTB-2 temperature sensors indicated 15.6°K (28.0°R) and 20.9°K (37.6°R), respectively, at this time. The average liquid temperature based on these measurements is therefore 18.2°K (32.8°R), which corresponds to an average liquid density of 73.1 kg/m^3 (4.56 lb/ft^3). The volume that would be occupied by liquid of this density, based on the measured hydrogen mass, is approximately 0.456 m^3 (16.1 ft^3), which indicates that approximately 0.022 m^3 (0.77 ft^3) of gas existed in the tank below the OS-2 waterline at this time. This indication is substantiated by the ullage pressure measurement of 9.76 N/cm^2 (14.2 psia), which is well below the saturation pressure of 12.1 N/cm^2 (17.5 psia) that corresponds to the RTB-2 temperature measurement. It was therefore concluded that bulk boiling was in progress when the OS-2 sensor was uncovered.

Subsequent to completion of the batch transfer test, a simulated space storability test was conducted. During the latter part of this test, the mixers were activated. Pressure and temperature time histories obtained from measurements made in the tank during operation of the mixers is shown in Fig. 7-14. It can be seen by inspection of this data that the solid transferred into the tank earlier had already melted when the mixers were activated. The ullage pressure and temperature reduction that occurred

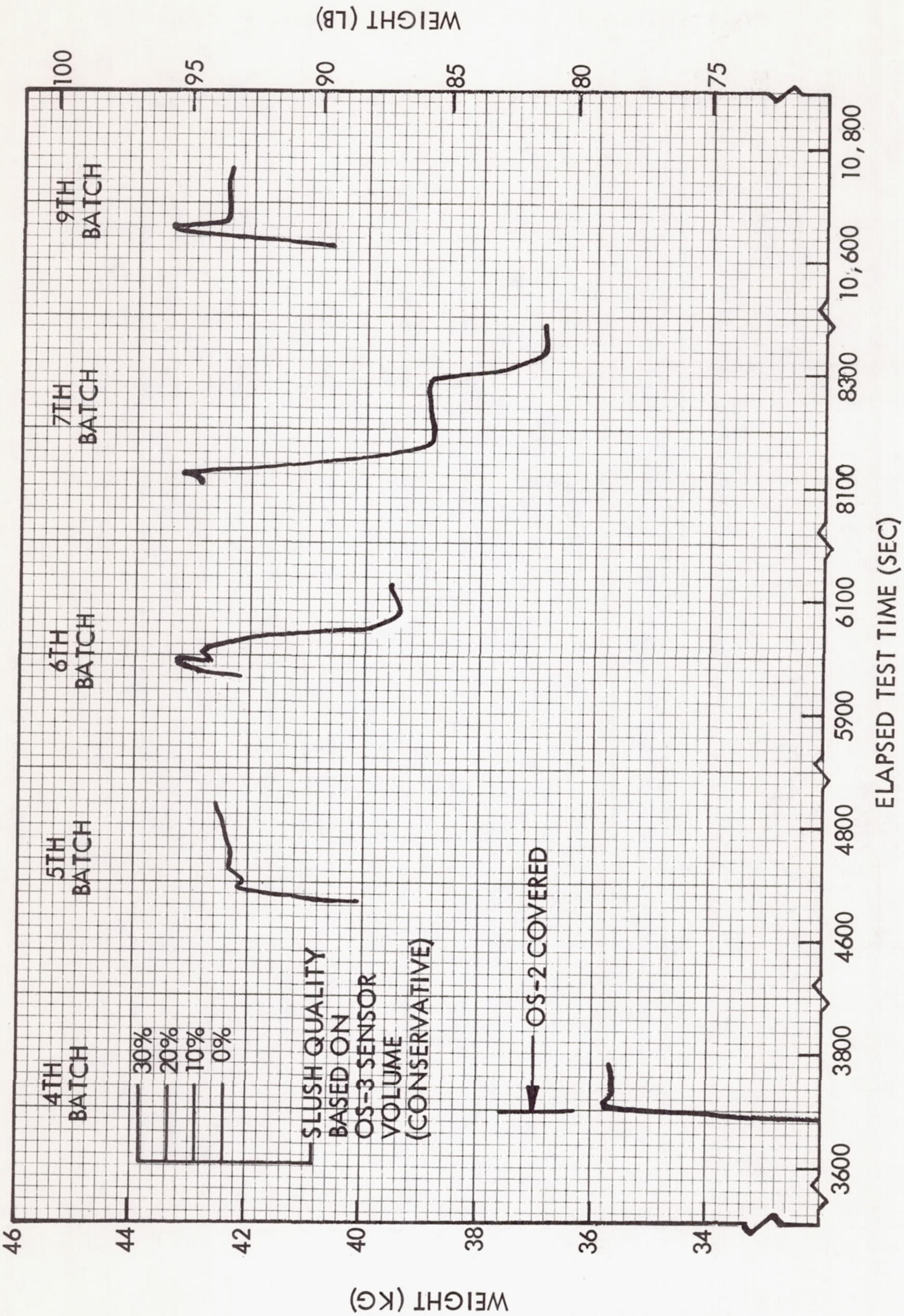

Fig. 7-13 Slush Mass During the Fourth Through the Ninth Batch Transfers (Third Flow Test)

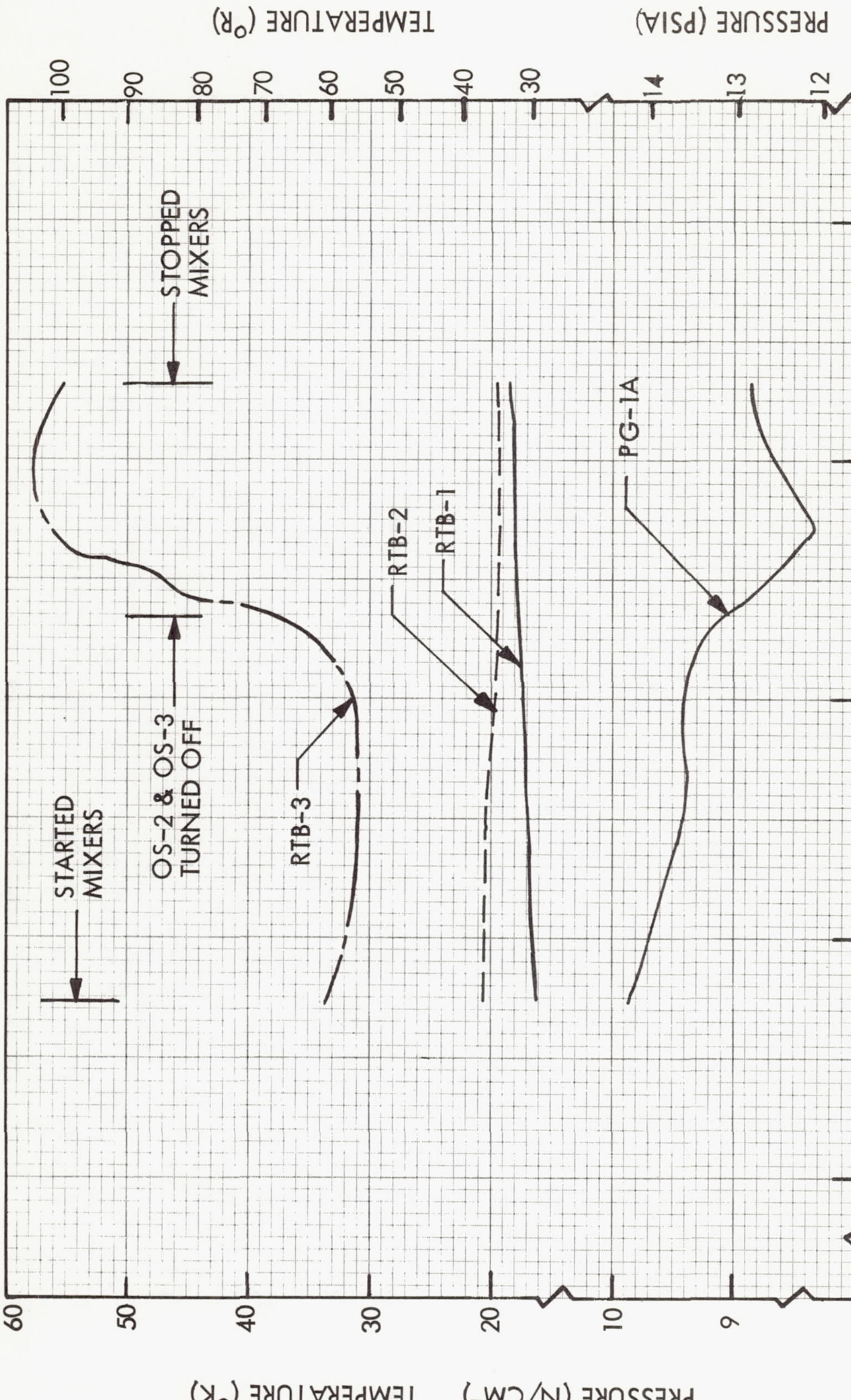

Fig. 7-14 Liquid Hydrogen Temperatures and Pressures During Mixing (Third Flow Test)

during the first 1600 sec of mixing was at a much slower rate than had been observed during the second flow test. In this instance, however, approximately 9.0 watts (30.6 Btu/hr) of energy was being introduced into the tank ullage gas by the active OS-2 and OS-3 optical sensors. These sensors were turned off at an elapsed test time of 14,340 sec and, as seen in Fig. 7-14, the ullage pressure decreased at a much higher rate for approximately 320 sec after that time. At an elapsed test time of approximately 14,000 sec, however, the tank ullage gas temperature, as measured by RTB-3, began to rise sharply and continued to rise for approximately the next 1000 sec. It is considered that this increase was probably due to recurrence of the "cold leak" that was observed to cause similar perturbations during the previous tests. During the mixer test, a total pressure collapse of approximately 1.5 N/cm^2 (2.2 psia) was observed, which again demonstrated that mechanical mixing is an effective technique that can be used to control liquid hydrogen tank pressures.

Results of the hydrogen draining sequence conducted at the end of the third flow test are presented in Fig. 7-15. The tank sensor outputs during draining can also be seen in Fig. 7-12. No significantly different effects were observed during this drain sequence when compared with that performed during the second flow test. It can be seen that some choked flow did occur initially as the unchilled line caused some initial flashing of liquid into vapor. The apparent high flowrates at approximately 11 sec of drain time, and again at 79 sec of draintime after the tank was empty, were considered to be due to two-phase flow in the transfer line, and should therefore be disregarded.

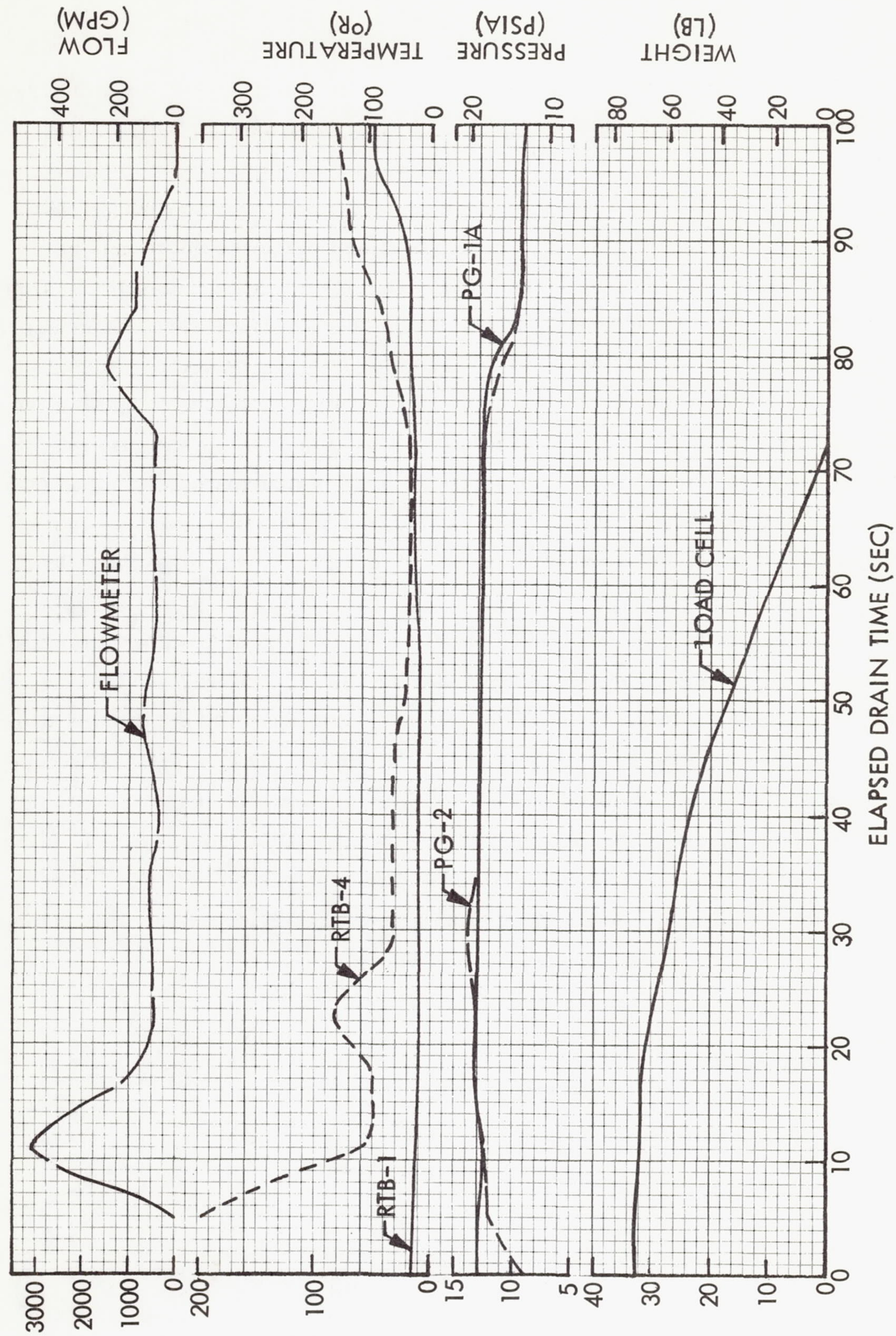

Fig. 7-15 Liquid Hydrogen Drain Data (Third Flow Test)

Section 8

CONVERSION FACTORS

Multiply	By	To Obtain
Atmospheres (atm)	10.1325	Newtons per square centimeter (N/cm^2)
Atmospheres (atm)	14.6959	Pounds force per square inch (psi)
British thermal units (Btu)	1054.8	Joules (Joule)
Btu per hour (Btu/hr)	0.292833	Watts (w)
Btu per hour-foot-°R (Btu/hr-ft-°R)	1.731×10^{-2}	Watts per centimeter-°K (w/cm °K)
Btu per pound (Btu/lb)	2.32597	Joules per gram (Joule/gm)
Centimeters (cm)	0.3937	Inches (in.)
Cubic feet (ft^3)	0.02832	Cubic meters (m^3)
Cubic feet (ft^3)	7.481	Gallons (gal)
Cubic meters (m^3)	35.31	Cubic feet (ft^3)
Cubic meters (m^3)	264.2	Gallons (gal)
Degrees Kelvin (°K)	1.8	Degrees Rankine (°R)
Degrees Rankine (°R)	0.556	Degrees Kelvin (°K)
Feet (ft)	0.3048	Meters (m)
Gallons (gal)	0.1337	Cubic feet (ft^3)
Gallons (gal)	3.785×10^{-3}	Cubic meters (m^3)
Inches (in.)	2.540	Centimeters (cm)
Inches (in.)	2.540×10^{-2}	Meters (m)
Joules (Joule)	9.481×10^{-4}	British thermal units (Btu)
Joules per gram (Joule/gm)	0.42993	Btu per pound (Btu/lb)
Kilograms (kg)	2.205	Pounds mass (lb or lbm)
Kilograms per cubic meter (kg/m^3)	6.243×10^{-2}	Pounds mass per cubic foot (lb/ft^3)
Kilometers (km)	0.539593	Nautical miles (nm)
Meters (m)	3.281	Feet (ft)
Meters (m)	39.37	Inches (in.)
Meters per second (m/sec)	0.101895	Pounds force-seconds per pound mass (lbf sec/lbm)
Millimeters (mm)	39.37	Mils (mil)
Millimeters of Mercury (mm Hg or torr)	1.934×10^{-2}	Pounds force per square inch (psi)
Mils (mil)	2.540×10^{-2}	Millimeters (mm)
Nautical miles (nm)	1.85325	Kilometers (km)
Newtons (N)	0.2248	Pounds force (lbf)
Newtons per square cm (N/cm^2)	9.869×10^{-2}	Atmospheres (atm)
Newtons per square cm (N/cm^2)	1.450	Pounds force per square inch (psi)
Pounds force (lbf)	4.448	Newtons (N)
Pounds force-seconds per pound mass (lbf-sec/lbm)	9.814	Meters per second (m/sec)
Pounds mass (lb or lbm)	0.4536	Kilograms (kg)
Pounds mass per cubic foot (lb/ft^3)	16.02	Kilograms per cubic meter (kg/m^3)
Pounds force per square inch (psi)	6.804×10^{-2}	Atmospheres (atm)
Pounds force per square inch (psi)	0.6895	Newtons per square cm (N/cm^2)
Pounds force per square inch (psi)	51.7	Millimeters of Mercury (mm Hg or torr)
Watts (w)	3.4152	Btu per hour (Btu/hr)
Watts per centimeter-°K (w/cm °K)	57.78	Btu per hour-foot-°R (Btu/hr-ft-°R)